STUDIES ON SPINY AMARANTH (AMARANTHUS SPINOSUS L.) INTERFERENCE WITH LETTUCE (LACTUCA SATIVA L.) AS INFLUENCED BY PHOSPHORUS FERTILITY ON HISTOSOLS

By

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To My Parents

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Studies were conducted to determine how spiny amaranth (*Amaranthus spinosus* L.) interference with lettuce (*Lactuca sativa* L.) grown on histosols would be influenced by soil phosphorus (P) fertility and P application method. Additive techniques were used in 3 field studies (spring 1991, fall 1991 and spring 1992) to test for the effects P application method (banded versus broadcast), weed density and duration of interference on lettuce yields. Phosphorus application by either method increased lettuce yields ca. 100% over controls not receiving P. Spiny amaranth biomass was less responsive to P. Duration of interference reduced lettuce yields in a quadratic fashion with broadcast P application in spring 1991 and 1992. With mid- to full-season interference, lettuce yields were reduced more with 4 weeds per 2.3 m than 1.

Lettuce tissue P concentrations explained the yield response to P fertilization; P being least with no added P, intermediate with banded P and highest with broadcast P. Lettuce yield loss due to weed interference was not explained by nutritional status.

Replacement techniques were used in 3 greenhouse experiments to study the effect of P fertility on competition between lettuce and spiny amaranth during the first 4 weeks of growth. Monocultures and 1:1 mixtures were used at total densities ranging from 2 to 32 plants per 113 cm^2. Competition was assessed based on analyses of individual plant weight, relative yields, relative crowding coefficients (RCC) and relative mixture response. Competitive interactions varied with experiments. When monoculture growth of the two species was comparable, lettuce was more competitive than spiny amaranth in mixture at all but the lowest P fertility level. When spiny amaranth growth in monoculture was 2 to 4 times greater than that of lettuce, the weed was the dominant competitor. However, relative yield analysis suggested that the competitive ability of lettuce was improved by increased P fertility. Competitive interactions were density dependent. As measured by the RCC, the intensity of interspecific competition increased with density; this density effect being species dependent. However, there were no interactions between density and P fertility in the analysis of interspecific competition.

CHAPTER 1
INTRODUCTION

During the period between 1986 and 1991, lettuce (*Lactuca sativa* L.) produced in Florida had an annual average value of more than 38 million dollars (Freie and Young, 1992). Greater than 90 percent of this production occurred on Everglades histosols. Most of the remainder was grown on histosols in the central region of the state.

Weed control is important in the production of quality lettuce (Ryder, 1979). On Florida muck soils, available weed control strategies are limited. For gramineous weeds, postemergence herbicides are available (Stall and Dusky, 1992). Broadleaf weeds, however, are an important weed problem on these soils (Dusky et al., 1988). Nonselective weed control between the crop rows can be obtained with a shielded application of paraquat (1,1′-dimethyl-4,4′-bipyridinium). However, weeds in the crop row remain uncontrolled with this measure. Soil applied herbicides are available for broadleaf weed control in lettuce on mineral soils; however, these are not recommended for use on muck soils (Dusky and Stall, 1992). Thiobencarb (S-[(4-chlorophenyl)methyl]diethylcarbamothioate) is one herbicide that can be used on these soils for weed control in lettuce

(Dusky et al. 1988). Its herbicidal activity at a given use rate was found to be less on histosols than on mineral soil (Braverman, Locasio, Dusky and Hornsby, 1990). This was attributed to greater soil adsorption and decreased mobility of the herbicide in the organic soil compared to the mineral soil (Braverman, Dusky, Locasio and Hornsby, 1990). However, thiobencarb efficacy is dependent upon environmental conditions (temperature and moisture) and there is a relatively small safety margin for lettuce.

Due to the lack of options, weed control in lettuce grown on muck soils is highly dependent on cultivation and hoeing. Hoeing requires a high labor input. Hoeing also results in damage to lettuce plants (Dusky and Stall, 1990). Information concerning the effect weed infestations have on a crop facilitates the decision making process of when to apply control measures (Thill et al., 1991). Such information might help to minimize labor costs and to reduce crop damage that would result from excessive hoeing. Such information for lettuce is scarce.

Crop mineral nutrition is important in the production of quality lettuce (Ryder, 1979). Relatively large amounts of phosphorus (P) fertilizer are required to obtain a lettuce crop of good quality and yield on high organic matter soils (Sanchez and Burdine, 1988). Current environmental and economic issues, however, compel growers to reduce fertilizer P use (Alvarez and Sanchez, 1991;

Sanchez et al., 1990). One promising approach to reduced fertilizer P application for lettuce is the use of a banded application (Sanchez et al., 1990).

One objective of this investigation was to characterize the effect of interference by spiny amaranth (Amaranthus spinosus L.), an important broadleaf weed species, on lettuce. Spiny amaranth was chosen for these studies because of its ubiquitous occurrence throughout the lettuce growing areas of Florida and because of the difficulty of controlling it in lettuce. A second objective was to determine how P fertilization practices would influence the effect of the weed on the crop. In following with these objectives, two series of studies were conducted. These studies are presented in chapters III and IV.

Chapter III of this investigation concerns field studies which were conducted to determine how density and duration of spiny amaranth interference affects lettuce yields. These factors were examined at several fertilizer P application options.

Chapter IV of this investigation presents studies on competition between lettuce and spiny amaranth during early growth. Competition is assessed in these studies under varied levels of P fertilizer amendment of muck soil. Several methods of analyzing the competitiveness of one species upon another are discussed.

CHAPTER 2
LITERATURE REVIEW

Interference and Competition

It has been stated that weed control measures "focus directly or indirectly on improving the competitive ability of crops with regard to weeds" (Spitters and Van Den Berg, 1982, p. 137). This is an example of how the term competition is commonly used to refer to the overall effect that weeds have on crop growth due to interactions between plants growing in close proximity to one another. Losses in crop yield or quality from interactions among weeds and crops form the basis of modern weed science (Radosevich, 1987). Radosevich and Holt (1984) discussed the existence of ten possible interactions, previously published by another author, that may occur between plants. These interactions have to do with the influence a plant might have on the environment of its neighbors and are collectively termed interference. Three of the interaction types, competition, amensualism (allelopathy) and parasitism are of a negative nature. These are also of particular importance to crop production. Competition refers to mutually adverse effects of organisms utilizing a resource

in short supply. Other definitions for the terms interference and competition are also found in the literature (e.g. Hall, 1974a) and these terms have even been used synonymously (Glauninger and Holzner, 1982).

In nonagricultural ecosystems plant competition is a phenomena influencing both the immediate and the future community. On a short term, it determines how individual plants will fare as compared to neighbors of both like and different species. On a longer term, competition is an important force influencing the higher plant composition of the ecosystem (Grime, 1979). In agricultural ecosystems, plant competition is commonly viewed as a factor influencing crop productivity (Radosevich and Roush, 1990), which implies a shorter term focus than the study of competition in nonagricultural ecosystems would take.

The study of plant competition in agriculture generally concerns the optimization of crop yield. One application of this concerns the determination of mixed cropping system characteristics that enable maximum crop productivity (Spitters, 1983). All components of the intended mixtures are of economic value to the grower. The study of competition, in this case, aims to achieve a optimal balance between the desirable components. Another application of the study of plant competition in agriculture concerns the case in which crop plants grow in mixture with plants that are not part of the intended crop. The study of competition

in this case would still concern the optimization of crop productivity. In contrast to the mixed cropping scenario, however, optimization is dependent on the productivity of only the desirable components of the mixture. The study of competition between weeds and agricultural crops is of this nature.

Conceptualization of weed competition with crops is linked to the methodology used in its study. General treatment of the topic often begins with a discussion of methodology (Radosevich and Roush, 1990; Spitters and van den Berg, 1982). There are two basic methods which have received considerable attention (Cousens, 1991; Radosevich, 1987). The replacement or substitutive series was advanced by the work of de Wit (1960) although it was reportedly established prior to this (Cousens, 1991). The additive study is the second principle method (Cousens, 1991; Radosevich and Roush, 1990). A third method, the area of influence, has been considered a special case of the additive study (Radosevich and Roush, 1990).

Each of these methods is useful for answering a unique set of questions (Cousens, 1991). The additive design addresses weed management concerns such as the establishment of relationships between weed density and crop yield and the comparison of weed species for their ability to suppress crop yields. The replacement design is used for determining which of two components of a binary mixture is the better

competitor. It is also utilized when study objectives include the identification of the nature of the interaction between the two components of the mixture (Cousens, 1991; Jolliffe et al., 1984; Radosevich, 1987). The area of influence approach is applicable for determining the effect of an individual weed on crop plants growing at various distances from the crop plant (Gunsolus and Coble, 1986).

Just as each of these basic methods has a specific purpose, limitations are also associated with each (Cousens, 1991). It was argued that these methods have been wrongfully criticized for these limitations. This is because the criticisms have assumed that the methods should provide more thorough analyses of competition than is achieved with them. Thus, much of the criticism would be better viewed as limitations to be recognized and accepted (Cousens, 1991). In light of this situation, modifications or extensions of these basic methods of analysis of plant competition have been proposed.

Two concerns that have been raised regarding the analysis of plant competition are that results are density dependent and that intraspecific and interspecific competition effects are not separable (Firbank and Watkinson, 1985; Jolliffe et al., 1984; Spitters, 1983). Variations on each of the replacement (Jolliffe et al., 1984) and additive (Rejmanek et al., 1989; Spitters, 1983)

approaches have been developed to address these limitations to the basic methods.

Conventional analysis of replacement series studies uses expected yields as a reference from which inferences about competition are made (Jolliffe et al., 1984; Rejmanek et al., 1989). Analysis based on expected yields does not permit the partitioning of interspecific and intraspecific competition effects in the overall analysis. Jolliffe et al. (1984) proposed the use of a "projected yield" as a reference against which competitive effects can be measured in a replacement series. This technique has been referred to as a "synthetic no-interaction approach" (Roush et al., 1989, p. 270). The projected yield is a hypothetical curve of how the yield of a monoculture would respond to plant density in the absence of intraspecific competition. Using this approach, intraspecific competition is quantified by comparison of actual monoculture yields with projected yields. The response of the individual species to mixture is measured by comparison of yield obtained in mixture with those of the monoculture. In order to address the question of the effect that density has on competitive relations, the method can be further expanded by conducting the replacement series at varied densities (Jolliffe et al., 1984; Paul and Ayres, 1987; Rejmanek et al., 1989).

The additive study methodology can be expanded to enhance competition assessment by a technique termed

"reciprocal yield analysis" (Rejmanek et al., 1989; Roush et al., 1989). Application of this approach involves the establishment of additive series for each of the mixture components of interest, which is termed a "complete additive design". These series can be established at each of several levels for the set density component of a series (Vleeshouwers et al., 1989). With this approach, mixtures of two or more components can be studied (Rejmanek et al., 1989). The effect of each component of the mixture on the other(s) can be assessed.

The results obtained in competition studies can be influenced by a number of factors (Aldrich, 1987) and basic methods are found to be biased with certain mixtures (Connolly, 1986). Studies have been conducted to compare some of the alternative approaches to competition analysis when applied to specific situations (Rejmanek et al., 1989; Roush et al., 1989). The reciprocal yield analysis technique was found in both studies to be useful for the assessment of interspecific versus intraspecific competition effects. The basic replacement series was considered in both studies to be inferior in describing competitive effects over several densities and in describing the effect of species proportions. In the study by Roush et al. (1989) the synthetic no-interaction approach was also evaluated. It was found to be superior for analysis of the influence of proportion on interspecific competition. The reciprocal

yield approach was preferred for the partitioning of interspecific and intraspecific competition effects and the measurement of interactions between density and proportion.

Factors Influencing Competition

Factors that have been found to influence plant competition include environment, plant emergence characteristics, growth rates and other components of plant size and function (Radosevich, 1987). Proximity of individual plants to others is directly influenced by density, spatial arrangement and species proportion, which are considered influential factors in the study of interactions between plants. Planting pattern has been found to influence competitiveness of crop plants with square and equilateral triangle patterns making crops more competitive than rectangular patterns (Aldrich, 1987).

Aldrich (1987) examined causes of variability found in results of weed density/crop yield studies from apparently similar situations. In agricultural crops, the amount of plant growth that has accrued up to any moment is density dependent at the start of the crop cycle and becomes density independent as time passes (for closed canopy crops). Biomass production rate is maximum once the transition has been made to the density independent stage. Environmental factors or factors related to weed presence may influence the time required to reach the density independent stage,

which in turn influences the length of time over which the maximum biomass production rate occurs.

The nature of acquisition of resources by plants can influence the potential onset of competition for them (Aldrich, 1987). Mobile resources in a given region of the soil may be used simultaneously by crop and weed plants whose root systems have not yet overlapped. On the other hand, relatively immobile resources, such as phosphorus, would only be taken up from soil in close proximity to roots of the individual plants. Consequently, competition for mobile resources could begin sooner than for less mobile ones.

Crop emergence timing relative to that of weeds can influence competitive interactions between the two. Elberse and deKruyf (1979) studied the influence of emergence timing on competition between lambsquarters (*Chenopodium album* L.) and barley (*Hordeum vulgare* L.) using a replacement study approach. Barley was sown at 7, 21 and 31 days after lambsquarters and three harvests were made for each sowing. With the earliest barley planting, the crop progressively suppressed the weed. The 21 day planting resulted in weed and crop coexisting with neither becoming dominant. For the latest planting the crop replaced the weed. Aldrich (1987) emphasized the importance of the effect of emergence timing as a source of variation in weed interference studies, pointing out that it can be difficult to control when

working with various species under field conditions. Temperature may influence growth rates and competitive ability of weed species differentially (Aldrich, 1987). Studies are cited in which redroot pigweed (*Amaranthus retroflexus* L.) grew faster and was more competitive than lambsquarters with increased temperature.

Factors for which Plants Compete

Of the factors that influence plant growth some are of a consumable nature (nutrients, water, CO_2, O_2 and light) while others are conditions, e.g. temperature (Radosevich and Holt, 1984). It is those of the first category for which competition might occur (Radosevich and Holt, 1984; Aldrich, 1987). An additional distinction is made that light is available in a fixed amount while water and nutrients, though available in limited amounts, can be manipulated by the grower (Glauninger and Holzner, 1982). Aldrich (1987) cites that environmental conditions would preclude competition for CO_2 and O_2. DeWit (1960) discussed space as a factor for which plants compete, contending that it is not feasible to separate out individual components. However, Glauninger and Holzner (1982) consider space to be just the combined effects of competition for light, nutrients and water. Nevertheless, competition for both below and above ground factors appears to be important. Wilson (1988) reviewed literature concerning studies in

which attempts were made to separate competitive interactions occurring between shoots from those arising in the root environment. Consideration of 47 cases led to the conclusion that both types of competition can be important although root competition is generally of greater importance.

Light is a resource that is "continuously available in a constant amount" (Glauninger and Holzner, 1982, p. 150). In situations where water and nutrients are adequate, light is the factor that will ultimately determine plant growth (Gardner et al., 1985). Competition for light begins when one plant begins to shade another (Glauninger and Holzner, 1982). Because light is nontransferable within a plant, shading of a portion of one plant by another results in the shaded region not receiving the resource (Aldrich, 1987). Characteristics such as stature, growth habit and ability to photosynthesize in less than full sunlight contribute to the ability of plant species to compete effectively with other species (Glauninger and Holzner, 1982). Well developed crop stands may offer sufficient light interception to provide significant reduction of weed development. Redroot pigweed biomass was found to be less in soybeans planted on 25 cm row spacings than when the crop was grown on 76 cm row spacings (Legere and Schreiber, 1989). With more closely spaced rows the canopy would close earlier. Weed species vary in their susceptibility to growth reduction due to

shading. Common purslane (<u>Portulaca</u> <u>oleracea</u> L.) is reportedly very susceptible while lambsquarters is much less so (cited in Glauninger and Holzner, 1982). For crops, early growth, height and density are important for successful competition with weeds to occur (Glauninger and Holzner, 1982).

Only a limited amount of information is available on the effects of weed interference on lettuce. This information has focused on temporal aspects of weed presence in the crop. Field studies in England demonstrated that when the crop was free of weeds at 3 weeks after emergence, no yield loss resulted from subsequent weed infestation (Roberts et al., 1977). In studies conducted in Florida, the effects of duration of weed interference was assessed for monospecies weed infestations of livid amaranth (<u>Amaranthus</u> <u>lividus</u> L.) at densities of 120 plants per m^2 and common purslane at 15 plants per m^2 (Shrefler et al., 1991). In the case of livid amaranth, if weeds were removed at 19 days after planting of the crop no yield loss occurred, whereas delaying weed removal an additional 15 days resulted in complete loss of marketable yield. In the case of common purslane, delaying weed removal from 16 to 37 days after planting of the crop resulted in a 36% decrease in marketable yield, which occurred in a linear fashion with time.

On high organic matter soils in Florida, relatively large amounts of phosphorus fertilizer are required for lettuce production (Sanchez and Burdine, 1988). This nutrient has been found to influence the outcome of plant competition in some instances (Buckeridge and Norrington-Davies, 1986; Kranz and Jacob, 1977; Weiner, 1980). However, no information is available concerning the effect P fertility would have on weed interference with lettuce.

The general objectives of the studies discussed herein, and as outlined in chapter I, are to characterize the effects of interference by spiny amaranth (*Amaranthus spinosus* L.) on lettuce and determine how P fertilization would, in turn, influence these effects. Studies in chapter III concern the effects of weed interference on the crop under field conditions as influenced by P fertilizer application method. The additive method of the study of weed interference was used in order to assess the impact of the weed on the crop. The effect of the duration of weed interference was assessed at 2 weed densities that fall within the range of what might be encountered under commercial production conditions.

Studies in chapter IV concern the determination of how P fertility influences the growth of each of the weed and the crop when grown in the presence of one another. A replacement study design at a series of densities was used for these studies. This design permits assessment of the

effects of competition on each species of the mixture. By conducting studies at several densities, the effect of plant density on competition, as assessed by the replacement design, can also be evaluated. In addition, this approach also permits analysis of competition using the synthetic no-interaction approach (Roush et al., 1989). The methodology used in this study, therefore, was chosen to enable some comparison of methods for use in the assessment of competition as influenced by P fertility.

CHAPTER 3
SPINY AMARANTH INTERFERENCE IN CRISPHEAD LETTUCE AS INFLUENCED BY PHOSPHORUS FERTILIZER APPLICATION METHOD

Introduction

Production of high yielding, quality lettuce (*Lactuca sativa* L.) requires the intensive management of a number of factors (Ryder, 1979), two important ones being weed control and mineral nutrition of the crop. While weed control is commonly employed in commercial lettuce production, detailed documentation of the effects of uncontrolled weed growth on lettuce is scarce. Some information concerning the effect weeds have on lettuce is found in studies in which herbicides and other control methods are evaluated (Dusky et al., 1988; Giannopolitis et al., 1989). Such studies indicate that substantial weed losses will occur if weeds are not controlled.

Studies specifically concerned with how weeds affect lettuce have also been reported. Field studies in England showed that densities of 65 weeds per m^2 resulted in complete loss of marketable yield when weeds were allowed to remain present in the crop (Roberts et al., 1977). Weed populations in these studies were comprised of a mixture of gramineous and dicotyledonous species. Elimination of weeds

by hand at 3 weeks after emergence of the crop, with no additional weed removal, was sufficient to prevent significant yield loss.

The effect of early season interference with crisphead lettuce by specific weed species has also been assessed (Shrefler et al., 1991). Livid amaranth (Amaranthus lividus L.) at 120 plants per m^2 did not affect marketable lettuce yield when removed 19 days after planting of the crop. Delaying weed removal an additional 15 days resulted in complete loss of marketable yield. Common purslane (Portulaca oleracea L.) at 15 plants per m^2 resulted in a reduction in the quantity of marketable lettuce heads as weed removal was delayed from 16 to 37 days after planting of the crop (Shrefler et al., 1991). Weed interference during this 21 day period resulted in a 36% yield decrease, which occurred in a linear fashion with time.

Weeds adversely affect crops due to competition for light, water and nutrients (Patterson, 1985). When water and nutrient availability are optimal, light is the factor which ultimately limits crop growth (Gardner et al., 1985). If sunlight interception by a plant is reduced due to shading caused by a neighbor plant then interference for light necessarily occurs (Aldrich, 1987). This is in contrast to the below-ground factors, i.e. nutrients and water, which may be available in excess of the consumptive capacity of the plants. Because competition for light is

the result of shading, the onset of this interaction is related to weed density. As weed density decreases, individual weeds will have to achieve greater size in order to cause comparable amounts of shading.

The sensitivity to shading which would occur in competition for light could be expected to vary with plant species. This is because plants differ in their capacity to use light in photosynthesis (Gardner et al., 1985). Leaves of plant species in which carbon is fixed via the C_4 pathway do not generally light saturate at full sunlight. Species of the C_3 type, on the other hand, commonly reach maximal photosynthetic levels at less than full sunlight. This was found to be the case for lettuce, a C_3 plant, well into the vegetative growth portion of the crop cycle (Sanchez et al., 1989). As lettuce approached maturity, however, photosynthetic photon fluxes equivalent to full sunlight were required for maximum carbon exchange rates.

Competitive interactions between plants may also take place through the root systems. As a means of assessing the relative importance of plant competition due to below-ground interactions versus those occurring above-ground, Wilson (1988) summarized the results of a number of studies found in the literature in which separation of root and shoot competition was attempted. These studies used partitions to isolate root systems or shoots between plants of mixtures in which competition was being studied. Wilson (1988)

concluded that both root and shoot competition were important although the former tended to be so more frequently.

Water is one below-ground factor for which competition between weeds and crops can occur (Aldrich, 1987; Griffin et al., 1989). Competition for water would occur when soil moisture is inadequate to provide the combined needs of weed and crop plants (Aldrich 1987). Soil moisture levels can also influence the nature of competition that occurs between plant species. Griffin et al. (1989) studied competition between soybean (*Glycine max* (L.) Merrill) and Florida beggarweed (*Desmodium tortuosum* Sw. (DC) under different soil moisture regimes. These experiments showed that at optimum levels of available soil water soybean was more competitive than the weed. Soybean, however, was more sensitive to decreased soil water potential than the weed. Consequently, at low levels of water availability the weed became more competitive than the crop.

Below-ground competition between different species can sometimes be attributed to the availability of mineral nutrients and nitrogen. In the previously discussed work by Wilson (1988), one category of study considered is where competition is evaluated at several levels of nutrient availability. Indices of competition that were calculated for each study evaluated were highest at low levels of nutrient availability as often as at high levels. No

generalization that competition was reduced by increased nutrient levels was possible.

Alkamper (1976) reviewed literature on the combined influence of weeds and fertilization on crop production. Based on this, he concluded that fertilization without weed control results in increased crop damage by weeds, except possibly in the case of low weed densities.

Soil fertility requirements for lettuce production on organic soils in Florida have been established (Sanchez, 1990). Phosphorus is applied based on quantitative analysis of soil for water extractable P. Once this value is obtained a corresponding fertilizer P rate can be determined from a calibration curve (Sanchez and Burdine, 1988). Inadequate soil P predictably results in sub-optimal lettuce yields (Sanchez et al., 1988).

In lettuce production on south Florida histosols fertilizer P is applied prior to planting the crop (Sanchez, 1990). Sanchez et al. (1990) demonstrated that fertilizer P is utilized with greater efficiency when applied in a 'band' instead of broadcast, the traditional application method. With the band application, fertilizer P is placed in line with the crop row, 5 cm below the soil surface. These studies showed that equivalent yields can be obtained with two thirds lower fertilizer P rates if the nutrient is applied in a band rather than broadcast.

Fertilizer P placement close to lettuce seeds has been shown to provide the additional benefit of an increase in seedling growth that can not be achieved when the fertilizer is mixed throughout the soil (Costigan, 1984). This response was attributed to the slow early growth of lettuce roots. Thus, close placement of fertilizer P resulted in a growth response to the nutrient even though root system development was still minimal.

Economic analysis of vegetable production in Florida suggests that reduced use of fertilizer P could render lettuce production unprofitable (Alvarez and Sanchez, 1991). Environmental concerns, among others, call for reduced fertilizer application due to its potential adverse effect on wetland ecosystems which are closely linked to agricultural lands. Band application of fertilizer P appears to be one means by which nutrient use rates could be reduced without reducing lettuce yields.

In anticipation of the adoption of a banded fertilizer P application practice, studies were carried out to determine how this might influence the impact of weed interference on lettuce. The weed selected for use in these studies was spiny amaranth (*Amaranthus spinosus* L.). Spiny amaranth is the most ubiquitous weed in lettuce production areas in Florida and difficult to control in the crop due to a lack of registered herbicides (Dusky et al., 1988). Since little detailed information on the effect of weeds on

lettuce is available, studies were designed to assess both the effect of weed density and duration of weed presence on the crop under several fertilizer P application regimes.

Several methods can be used to assess interference between different plant species when grown in mixture (Cousens, 1991). There are two basic methods which have received considerable attention (Cousens, 1991; Radosevich, 1987). The replacement or substitutive series was advanced by the work of de Wit (1960) although it was reportedly established prior to this (Cousens, 1991). The additive study is the second principle method (Cousens, 1991; Radosevich and Roush, 1990). Each of these methods is useful for answering a unique set of questions (Cousens, 1991). The additive design addresses weed management concerns such as the establishment of relationships between weed density and crop yield and the comparison of weed species for their ability to suppress crop yields. The replacement design is used for determining which of two components of a binary mixture is the better competitor. It is also utilized when study objectives include the identification of the nature of the interaction between the two components of the mixture (Cousens, 1991; Jolliffe et al., 1984; Radosevich 1987). An additive design was chosen for these studies since the principle objective was to determine the effect weeds have on the crop under the different fertilizer P application regimes.

Materials and Methods

Three field experiments were conducted during 1991 and 1992 at the Everglades Research and Education Center at Belle Glade, Florida as shown in Table 3.1. Soil at the study site is classified as a Pahokee series muck [Euic, hyperthermic Lithic Medisaprists (Soil Survey Staff, 1978)]. Prior to selecting the field location for each experiment, soil was sampled and analyzed for nutrients as described by Sanchez (1990). Soil chemical characteristics of the fields in which the experiments were conducted, which were selected for low P fertility, are given in Table 3.2. Fertilizer application of all nutrients except P was made to the entire study area as recommended based on soil test results. Phosphorus application, as triple superphosphate, was also made based on soil-test recommendation. Instead of being applied to the entire study area, fertilizer P was applied as an experimental treatment. Specific treatments used were; 1) no added P, 2) broadcast applied P and 3) band applied P. Broadcast applied P was distributed evenly on the soil surface and mixed in the soil with a disk harrow. Where P was applied as a band treatment in the 1991 experiments, one third the amount of P was used, on a per plot basis, as was used in the broadcast treatments. In 1992 the P fertilizer rate was increased to one half of the

Table 3.1 Schedule of procedures performed in the spring 1991, fall 1991 and spring 1992 experiments.

	Experiment		
Procedure	Spr. 1991	Fall 1991	Spr. 1992
	- - - -	date - - - -	
Apply broadcast fertilizers[a]	2/27	10/10	2/19
Apply banded P fertilizer	3/1	10/28	2/21
Plant	3/1	10/29	2/21
Thin crop stand	3/22	11/26	3/17
Establish weed densities	3/22	11/28	3/23
Harvest crop	5/8	1/8	4/27

[a]Potassium and micronutrients applied to the entire study area. Phosphorus applied broadcast as an experimental treatment.

Table 3.2 Soil chemical characteristics of the study sites and fertilizer phosphorus application rates in the spring 1991, fall 1991 and spring 1992 experiments.

			Phosphorus application[b]	
Experiment	pH	Pw[a]	broadcast	band
			--- Kg · ha^{-1} ---	
spring 1991	6.2	3	1320	440
fall 1991	6.6	3	1320	440
spring 1992	6.1	3	1320	660

[a]Water extractable phosphorus soil test index (Sanchez, 1990).

[b]Phosphorus applied as triple superphosphate.

amount of the broadcast application. A pressed bed planting system was used (Lucas, 1982). Fertilizer P for the banded treatments was applied during the bed formation process. This was done in such a way that a fertilizer band about 8 cm wide was placed 5 cm below the soil surface, in line with, and centered on, the crop row. Beds were constructed on 91 cm centers and had a width of 48 cm at the top. Crisphead lettuce 'Southbay' (Guzman, 1984) was direct seeded two rows to a bed. Seeding dates are given in Table 3.1. Rows were spaced 30.5 cm apart. Pelleted lettuce seed was sown in groups of three closely spaced seed every 30 cm of row. Plants were thinned to 1 every 30 cm at the times indicated in Table 3.1.

Spiny amaranth densities of 1 and 4 plants per 2.3 m of bed were established by selective removal of unwanted weeds from the naturally arising seedling population. The dates at which selective weed removal was performed are given in Table 3.1 and will be referred to as 'plot establishment'. The weeds kept in the plots were located on top of the bed and in the region in between the two crop rows. Once established, plots were maintained free of unwanted weeds by hand weeding or hoeing.

Following plot establishment, duration of weed interference treatments were achieved by removal of weeds from plots at various intervals. Weed removal timings for the spring 1991, fall 1991 and spring 1992 studies were 7,

21, 35 and 49 days, 7, 17, 28 and 36 days and 6, 16, 27 and 36 days, respectively. Following removal of spiny amaranth, these plots were maintained free of all weeds. Spiny amaranth plants removed from plots were dried at 60 C. Dry weights were obtained as a measure of biomass. Nutrient composition analysis was conducted on spiny amaranth of the different removal times.

A randomized complete block experimental design with four replications and with a split plot treatment arrangement was used for each experiment. Phosphorus application method comprised the main plots. A complete factorial arrangement of the weed densities and removal times constituted the subplots. There was a weed-free check plot for each P application regime. Individual plots consisted of a 9.1 m long section of raised bed. Subplots were separated by a weed-free bed which was planted to lettuce.

Lettuce harvest was timed so that the most mature lettuce plants would be harvested as late as possible without becoming excessively hard or cracked due to over maturity. Harvest dates are given in Table 3.1. Fifteen to 20 lettuce heads were harvested from each plot. In the spring of 1991, 10 heads were taken from each side of the bed. Lettuce heads were cut such that several of the outermost leaves were discarded. In the fall 1991 and spring 1992 studies lettuce was harvested from the western

side of the bed and with all intact leaves attached. Lettuce heads were counted and weighed. After the initial weighing of lettuce in the fall 1991 and spring 1992, a second weight was obtained following removal of the wrapper leaves (outer leaves which fall free from the head). Lettuce yield data were analyzed using analysis of variance techniques (Steele and Torrie, 1980) and SAS General Linear Models software (SAS Institute Inc., 1987). Lettuce yield data for the weed-free subplots were used as a control for each of the two weed density treatments. Duration of weed interference effects were analyzed with regression techniques (Freund et al., 1986). Regression analyses were performed on data means. Interactions between main effects were assessed using least squares means analysis and paired means comparisons (SAS Institute Inc., 1987).

Spiny amaranth biomass data were analyzed using techniques similar to those used for lettuce. Prior to analysis, amaranth data were log transformed after adding 1 to the data values. This was done because correlation of means and residuals was suggested by plotting residual values (Freund et al., 1986). Logarithmic transformation is appropriate when data for which values differ by a large magnitude are to be analyzed with analysis of variance (Steele and Torrie, 1980). This transformation resulted in residual plots which appeared to be of random distribution.

Samples of 4 to 6 lettuce plants were kept from each plot for nutrient composition analysis. In the spring of 1991 and 1992 heads were kept as harvested. In the fall of 1991 trimmed heads were used. Lettuce heads of these samples were cut up, dried and stored at 60 C.

Weed and lettuce samples to be used for nutrient analysis were ground in a stainless steel outfitted laboratory mill to pass through a 1 mm mesh sieve. Samples were thoroughly mixed following grinding and a subsample of the ground material was used for analysis. Subsamples were wet ashed as described by Wolf (1982). Nitrogen was determined by a micro-Kjeldahl method (Bremner and Mulvaney, 1982), P was determined colormetrically and K, Ca, Mg, Zn, Fe, Mn and Cu by atomic absorption spectrophotometry. Nutrient concentration data in lettuce and spiny amaranth were analyzed using the techniques discussed for lettuce yield and weed biomass data. Micronutrient data for lettuce and spiny amaranth are in Appendix A.

Results and Discussion

Spiny Amaranth Growth

The effects of P application (PA), weed density (WD) and duration of weed interference (DWI) on spiny amaranth biomass (on a per plant basis) for the spring 1991, fall 1991 and spring 1992 experiments are shown in Table 3.3. Substantially greater biomass was achieved in the spring

Table 3.3 The effect of P application, weed density, duration of weed interference and their interactions on spiny amaranth biomass in the spring 1991, fall 1991 and spring 1992 experiments.

Main Effect[ab]	Experiment		
	Spring 1991	Fall 1991	Spring 1992
	- - - - biomass ($g \cdot plant^{-1}$) - - - -		
PA			
None	49.9a[c]	5.9	55.8
Band	60.7b	6.0	69.0
Broadcast	57.4b	4.9	67.2
Signif.[d]	**	ns	ns
WD			
Low	65.0	6.8	70.7
High	47.0	4.5	57.3
Signif.	ns	***	***
DWI			
1	0.1	0.1	1.2
2	3.7	1.2	8.0
3	55.9	7.4	55.5
4	169.2	13.8	191.3
Signif.	***	***	***
Interactions			
	- - - - level of significance - - - -		
PA x WD	ns	ns	ns
PA x DWI	**	ns	***
WD x DWI	ns	ns	ns
PA x WD x DWI	ns	ns	ns

[a]Main effects are P application (PA), weed density (WD) and duration of weed interference (DWI). Low and high weed densities are 1 and 4 spiny amaranth plants per 2.3 m of bed. Durations of weed interference, in days after plot establishment, are (7, 21, 35 and 49), (7, 17, 28 and 36) and (6, 16, 27 and 36) for experiments 1, 2 and 3, respectively.

Table 3.3--continued.

[b]Analysis performed on log transformed data. Log transformation was made after addition of 1 to data. Non-transformed means are presented.

[c]Phosphorus application means within a column followed by a common letter are not significantly different at alpha=0.05 based on Duncan's Multiple Range Test.

[d]Significance for the main effect.

1991 and 1992 studies than in the fall of 1991. This can be attributed to the late time of establishment of the amaranth relative to the crop in the fall of 1991 (Table 3.1). The amaranth seedling emergence was very sparse in the fall 1991 experiment until two to three weeks after the crop was planted. This may have been due to moisture at the soil surface being inadequate for weed seed germination to occur. There was less than 1.2 cm of rainfall during the first 14 days following planting in the fall 1991 experiment while in the 1991 and 1992 spring experiments there was 2.6 and 3 cm, respectively, during the same period. In the spring 1992 study, plots were also established later than in the spring 1991 study (Table 3.1). In this case, however, amaranth per plant biomass at the first weed removal time was about 10 times greater than in the other studies (1.2 g per plant in 1992 versus 0.1 g per plant in the 1991 studies) (Table 3.3). In the fall 1991 experiment, only the main effects DWI and WD affected amaranth biomass (Table 3.3). Effects of DWI reflect the influence of plant age on biomass. Weed biomass per plant was 50% greater (6.8 versus 4.5 g per plant) under low than high weed density (Table 3.3). A density affect also occurred in the spring 1992 experiment such that amaranth biomass was 20% greater under low than high weed density. These reductions in biomass at the high weed density can likely be attributed to increased intraspecific competition. Classic plant population biology

studies show an inverse relationship between plant density and yield of individual plants in a population (Firbank and Watkinson, 1990).

In the spring 1991 and 1992 experiments there were significant interactions between PA and DWI on weed biomass. The effect of PA and DWI in the spring 1991 experiment is given in Table 3.4. Biomass of amaranth removed from lettuce at 21 days after plot establishment was greater where P was applied banded or broadcast than where no P applied. The effect of PA and DWI in the spring 1992 experiment is given in Table 3.5. Phosphorus application was found to affect amaranth biomass only in the case of the final DWI. When weeds were present until time of harvest of the crop, weed biomass under the banded P application was greater than where no P was added.

In general, the principle factors affecting spiny amaranth biomass were the length of time it was grown (DWI) and the density at which it was grown. While there is some evidence of a positive response to P application, this was not the case in the fall 1991 experiment (Table 3.3) or at the majority of the durations of weed interference in the spring studies (Tables 3.4 and 3.5). Thus, under the low P fertility conditions of these experiments, spiny amaranth growth, as reflected in per plant biomass, was similar with or without the addition of fertilizer P. This is in contrast to another weedy amaranthus species, redroot

Table 3.4 The effect of fertilizer phosphorus application on spiny amaranth biomass in the spring 1991 experiment.

Phosphorus Application	Duration of weed interference[a] 7	21	35	49
	- - - biomass (g · plant^{-1}) - - -			
None	0.07a[bc]	1.9 a	46.8a	165a
Banded	0.1 a	3.97b	64.6a	174a
Broadcast	0.14a	5.2 b	56.4a	168a

[a]Duration of weed interference in lettuce in days after plot establishment.

[b]Values within a column followed by the same letter are not different based on paired means comparison at alpha = 0.05.

[c]Analysis performed on log transformed data. Log transformation was made after adding 1 to data values. Non-transformed means are presented in the table.

Table 3.5 The effect of fertilizer phosphorus application on spiny amaranth biomass in the spring 1992 experiment.

Phosphorus Application	Duration of weed interference[a] 6	16	27	35
	- - - biomass (g · $plant^{-1}$) - - -			
None	1.50a[bc]	8.55a	55.0a	158a
Banded	1.05a	8.34a	59.8a	215b
Broadcast	1.08a	7.20a	51.5a	201ab

[a]Duration of weed interference in lettuce in days after plot establishment.

[b]Values within a column followed by the same letter are not different based on paired means comparison at alpha = 0.05.

[c]Analysis performed on log transformed data. Log transformation was made after adding 1 to data values. Non-transformed means are presented in the table.

pigweed (_Amaranthus_ _retroflexus_ L.), which was found by Hoveland et al. (1976) to be one of the more P responsive weeds of several that were studied. Phosphorus uptake variability is known to occur between plants of different species (Chapin and Bieleski, 1982; Hoveland et al., 1976). The effect of P fertility on biomass production by 17 plant species occurring as weeds in southern United States was studied (Hoveland et al. 1976). Considerable variation was found among the weed species. Those species exhibiting greatest response to P also showed the most severe deficiency under low P conditions. Variation in P uptake capacity by plants has been attributed to root size differences (Lindgren et al., 1977) and the presence of root hairs (Itoh and Barber, 1983). Spiny amaranth apparently has a root system which is well adapted to low P conditions.

Lettuce Yields

The effects on lettuce yields of phosphorus application, weed density and duration of weed interference and their interactions are shown in Table 3.6. Lettuce yields are presented on a weight per plant basis. In the fall 1991 experiment no interactions were found between the main effects (Table 3.6). In this experiment, application of P and duration of weed interference affected lettuce yields. Yields obtained with band and broadcast application were not found to differ. Regardless of the method used, P

Table 3.6 The effect of P application, weed density, duration of weed interference and their interactions on lettuce yields in the spring 1991, fall 1991 and spring 1992 experiments.

Main Effect[a]	Experiment: spr. 1991	fall 1991[b] -trim	fall 1991[b] +trim	spr. 1992 -trim	spr. 1992 +trim
	- - - - Lettuce Yield (kg · plant^{-1}) - - - -				
PA					
None	0.34a[c]	0.42a	0.28a	0.57a	0.43a
Band	0.65b	0.89b	0.67b	1.01b	0.78b
Broadcast	0.70b	0.93b	0.68b	1.07b	0.83c
Signif.[d]	***	***	***	***	***
WD					
Low	0.58	0.74	0.54	0.91	0.70
High	0.53	0.75	0.54	0.85	0.66
Signif.	***	ns	ns	***	***
DWI					
1	0.60	0.76	0.55	0.92	0.71
2	0.60	0.75	0.55	0.94	0.73
3	0.55	0.77	0.55	0.92	0.71
4	0.54	0.76	0.54	0.84	0.65
5	0.51	0.69	0.50	0.78	0.60
Signif.	**	*	ns	***	***
Interactions	- - - - - level of significance - - - - - - -				
PA x WD	ns	ns	ns	ns	ns
PA x DWI	*	ns	ns	ns	*
WD x DWI	***	ns	ns	***	***
PA x WD x DWI	ns	ns	ns	ns	ns

[a]Main effects are P application (PA), weed density (WD) and duration of weed interference (DWI) following plot establishment. Low and high weed densities are 1 and 4 plants per 2.3 m of bed, respectively. Durations of weed interference 1, 2, 3, 4 and 5 correspond to numbers of days after plot establishment of (0, 7, 21, 35 and 49), (0, 7,

Table 3.6--continued.

17, 28 and 36) and (0, 6, 16, 27 and 36) for the spring 1991, fall 1991 and spring 1992 experiments, respectively.

[b]Yields for untrimmed (-trim) and trimmed (+trim) lettuce.

[c]Phosphorus application means within a column followed by a common letter are not significantly different at alpha=0.05 based on Duncan's Multiple Range Test.

[d]Significance of the main effect.

application resulted in 2.2 and 2.4 times greater yields of untrimmed and trimmed lettuce, respectively, than when no P was applied. Duration of weed interference also had a significant effect on yield of untrimmed lettuce (Table 3.6). No meaningful trend over time was found however. Yields were consistent for the durations of weed interference of 0 through 28 days and appeared to decrease only when amaranth was present through harvest of the crop (36 days after plot establishment).

In the spring 1991 and 1992 experiments, P application resulted in significant lettuce yield increases (Table 3.6). In the 1992 experiment no differences were found between the band and broadcast application methods for untrimmed lettuce. Untrimmed lettuce yields were an average of 82% greater when P was applied, regardless of the application method. For spring 1991 yield, and trimmed yield in 1992, interactions occurred between PA and DWI (Table 3.6). The affect of PA and DWI in the spring of 1991 is shown in Figure 3.1. Phosphorus application by either method resulted in greater lettuce yields at all durations of weed interference. Broadcast application resulted in greater yields than band application in weed-free lettuce but not where weeds were present for any duration. Duration of weed interference had a significant effect on lettuce where P was applied broadcast but not where it was applied in a band or not applied at all.

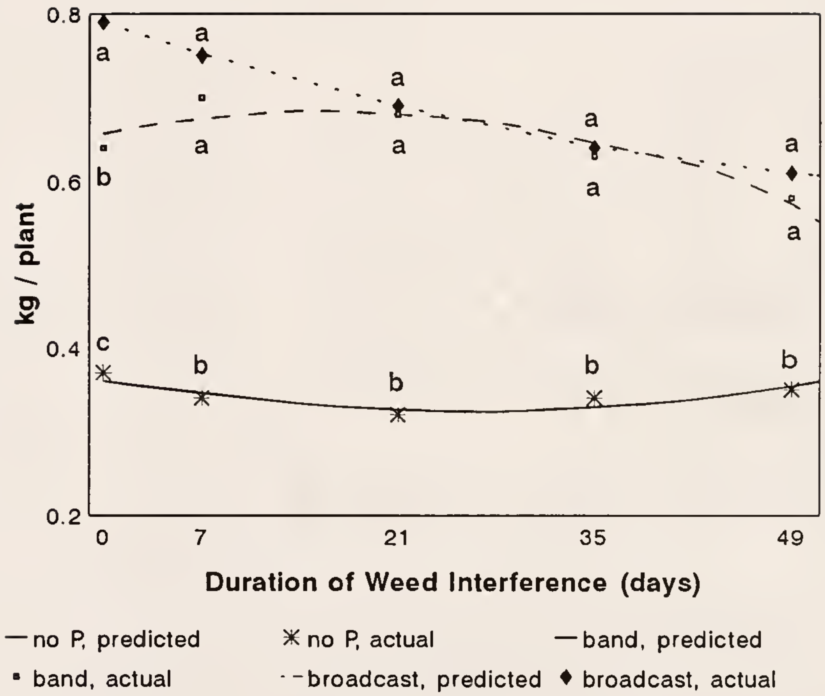

Figure 3.1 The effect of phosphorus fertilizer application and duration of weed interference on lettuce yields in the spring 1991 experiment. Actual means and regressions of yield on durations of weed interference are shown. Regression equations of yield versus time for no added P, band applied P and broadcast applied P are $Y=0.364-0.003X+0.000058X^2$ ($R^2=0.81$, not significant), $Y=0.657+0.0031X-0.0001X^2$ ($R^2=0.86$, not significant) and $Y=0.789-0.00057X+0.00004X^2$ ($R^2=0.99$, sig. at $p=0.001$), respectively. Actual values associated with a common letter at a given duration are not different at alpha=0.05 based on paired means comparisons.

The interaction of PA and DWI for trimmed lettuce yields in the spring 1992 study is shown in Figure 3.2. Phosphorus application by each of the methods resulted in increased yields at all durations of weed interference. Broadcast application resulted in greater yields than band application in weed-free (duration of weed interference equal to 0) lettuce but not where weeds were present for any duration. Duration of interference had a significant effect on lettuce yields both in the case of no added P and in the case of the broadcast application.

Lettuce responded to P application as would be expected based on the results of Sanchez et al. (1990). Phosphorus application by either the band or broadcast method resulted in substantial yield increases over those obtained where no P was applied. Analysis of the spring 1991 yield data suggested that slightly greater yields were obtained with the broadcast than the band application. For the spring 1992 study the P fertilizer rate in the band application was increased from 0.33 to 0.5 of that used in the broadcast application (Table 3.2). In spite of this modification, yields were still slightly greater for the broadcast application in the weed-free lettuce. It is not clear why this yield difference occurred in the weed-free plots.

In the fall 1991 experiment lettuce yields were not found to be differentially affected by weed density (Table 3.6). Lettuce yields in spring 1991 and 1992 were less

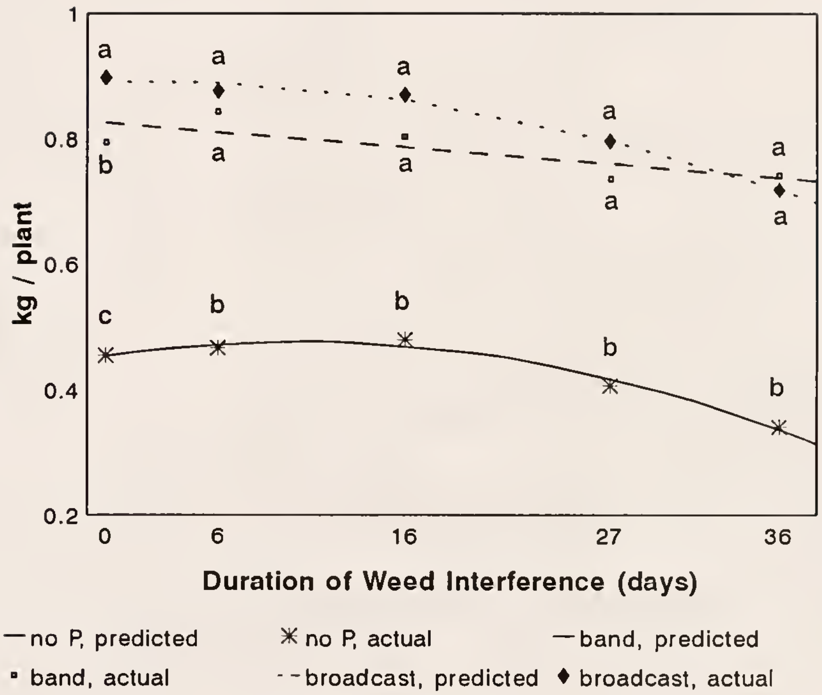

Figure 3.2 The effect of phosphorus fertilizer application and duration of weed interference on trimmed lettuce yields in the spring 1992 experiment. Actual means and regressions of yield on durations of weed interference are shown. Regression equations of yield versus time for no added P, band applied P and broadcast applied P are $Y=0.454+0.0043X-0.00021X^2$ ($R^2=0.98$, significant at $p=0.05$), $Y=0.825-0.00245X$ ($R^2=0.65$, not significant) and $Y=0.891+0.00056X-0.000149X^2$ ($R^2=0.99$, sig. at $p=0.05$), respectively. Within given durations, actual values associated with common letters are not different at alpha=0.05 based on paired means comparisons.

under high weed density than low weed density. There were also interactions between weed density and duration of weed interference in each of the spring experiments. The effect of WD and DWI on yields in the spring 1991 experiment is shown in Figure 3.3. Under high weed density, lettuce yields decreased in a linear fashion with increasing duration of weed interference. Under low weed density there was no significant effect of duration of weed interference on lettuce yields.

For the spring 1992 experiment the effects of WD and DWI are shown in Figure 3.4 for untrimmed yields and in Figure 3.5 for trimmed yields. Under each of the weed densities, untrimmed and trimmed lettuce yields decreased in quadratic fashions with increased duration of weed interference. The effect of high weed density was more pronounced than that of low weed density for each of untrimmed and trimmed lettuce yields.

In the fall 1991 experiment lettuce yields were essentially not affected by spiny amaranth (Table 3.6). In this experiment, the emergence of spiny amaranth relative to that of the crop occurred later than in the spring 1991 experiment. In the spring 1991 study, plots were established at 3 weeks after planting of the crop (Table 3.1). In the fall, weeds were not large enough for plots to be established until 4 weeks after the crop was planted. The final spiny amaranth biomass obtained in the fall 1991

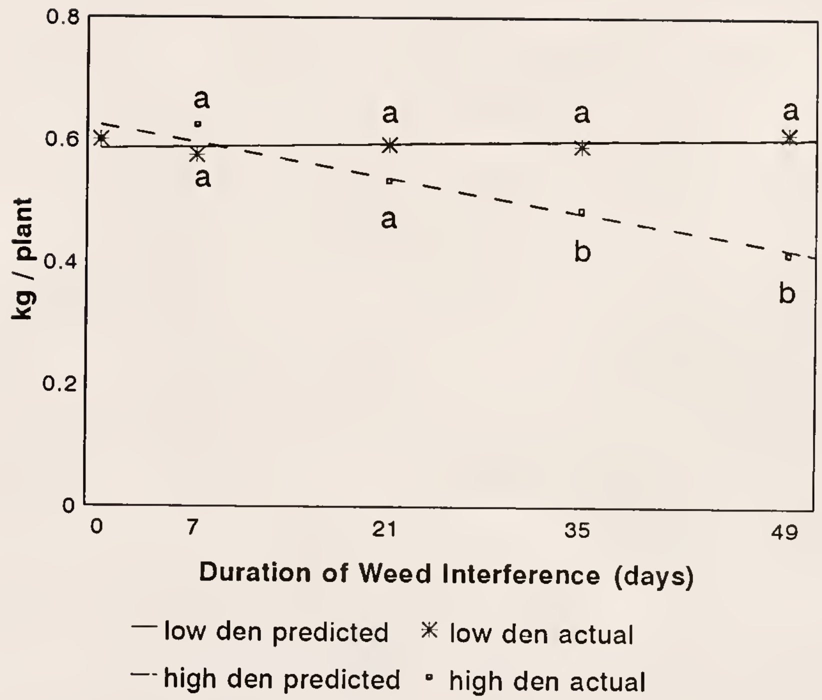

Figure 3.3 The effect of weed density and duration of weed interference after plot establishment on lettuce yields in the spring 1991 experiment. Actual means and regressions of yield on duration of weed interference are shown. Regression equations of yield versus time for low and high weed densities are Y=0.586+0.0003X (R^2=0.27, not significant) and Y=0.624-0.0041X (R^2=0.95, sig. at p=0.01), respectively. Within given durations, actual values associated with common letters are not different at alpha=0.05 based on paired means comparisons.

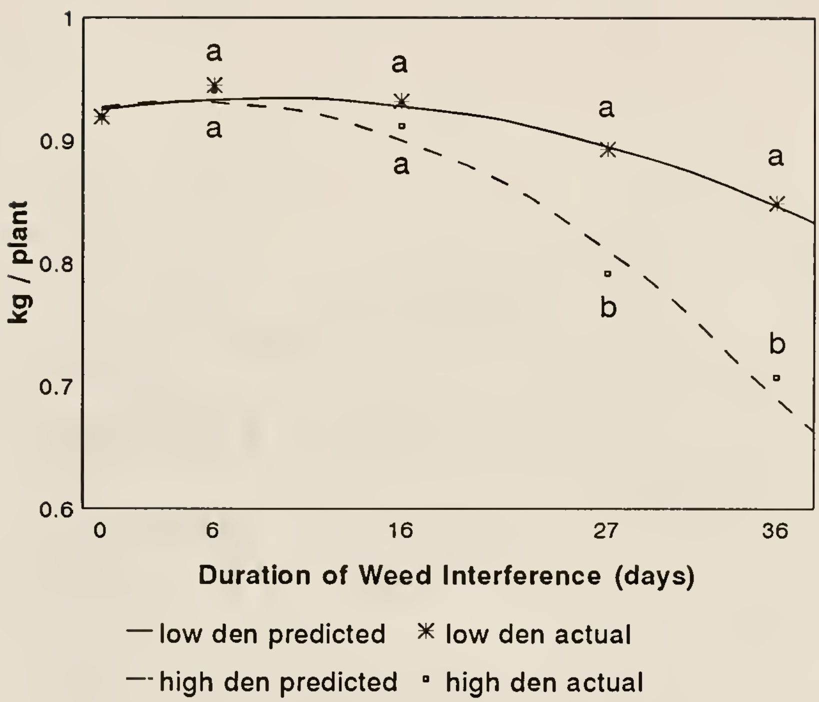

Figure 3.4 The effect of weed density and duration of weed interference on untrimmed lettuce yields in the spring 1992 experiment. Actual means and regressions of yield on durations of weed interference are shown. Regression equations of yield versus time for low and high weed densities are $Y=0.925+0.00207X-0.000118X^2$ ($R^2=0.96$, significant at $p=0.05$ and $Y=0.927+0.00218X-0.00024X^2$ ($R^2=0.86$, significant at $p=0.05$), respectively. Within given durations of weed interference, actual values associated with common letters are not different at alpha=0.05 based on paired means comparisons.

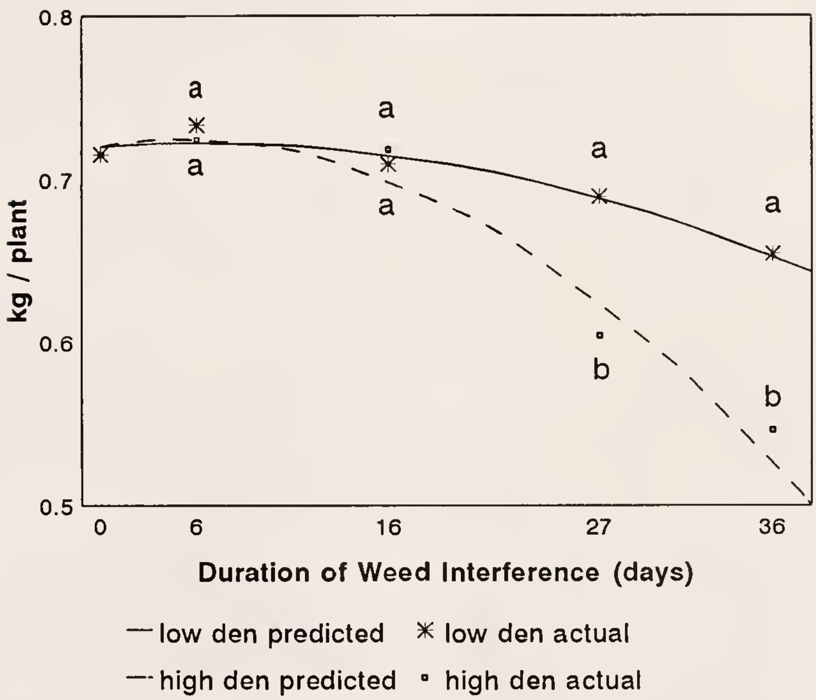

Figure 3.5 The effect of weed density and duration of weed interference after plot establishment on trimmed lettuce yields in the spring 1992 experiment. Actual means and regressions of yield on durations of weed interference are shown. Regression equations of yield versus time for low and high weed densities are $Y=0.72+0.00086X-0.000076X^2$ ($R^2=0.95$, significant at $p=0.05$) and $Y=0.72+0.0018X-0.0002X^2$ ($R^2=0.96$, significant at $p=0.05$), respectively. Actual values associated with a common letter at a given duration are not different at alpha=0.05 based on paired means comparisons.

experiment was only 8% and 7%, respectively, of that achieved in the spring 1991 and spring 1992 studies (Table 3.3).

Crop plants are often found to have critical weed-free periods (Zimdahl, 1980). If the crop is maintained free of weeds during such critical periods, yield losses to weeds do not occur. For lettuce, Roberts et al. (1977) found that if the crop was free of weeds at 3 weeks after emergence of the crop, yields would not be affected by subsequent weed emergence. It appears that in the fall 1991 experiment weed establishment did not take place within the critical period for crisphead lettuce.

In the spring experiments lettuce yields were reduced most when spiny amaranth was present at high densities throughout the season until the time of harvest of the crop. Under such conditions, yields were reduced by 30% in the spring of 1991 (Figure 3.3) and by 20% in the spring of 1992 (Figures 3.4 and 3.5). The apparently greater yield reduction in 1991 than 1992 may be related to the manner in which yield reductions occurred. Yields decreased in a linear fashion with duration of weed interference in the spring of 1991, suggesting that weeds began to affect yields beginning with the earliest durations of weed interference. In 1992, yield reduction occurred in a curvilinear fashion (Figures 3.4 and 3.5), which suggests that amaranth did not

begin to affect lettuce yields as early as in the spring 1991 study.

The onset of crop loss to weed competition can be attributable to variation in prevailing environmental conditions and resource availability (Zimdahl, 1980). For example, competition has reportedly been shown to limit crop yield earlier on when moisture availability is the limiting growth factor rather than light. Timing of the onset of competition has also been attributed to nutrient availability, with crop yield loss occurring earlier under high levels of nutrient availability. It may be that a factor such as these may have resulted in spiny amaranth competition beginning to have an affect on lettuce yield earlier in the spring of 1991 than in 1992.

Under low weed density lettuce yields were affected only in the 1992 experiment even though weed biomass achieved in the two spring studies was comparable (Table 3.3). It is not clear why yields were reduced by the low weed density in the spring of 1992 but not in 1991. One possibility is that lettuce growing under the conditions of the 1992 study was more susceptible to the effects of interference by spiny amaranth. Lettuce in the spring 1991 experiment was only partially trimmed in contrast to the trimmed lettuce of the 1992 study. Direct comparison of yields for the two spring studies cannot be made due to differences in the degree of trimming used at harvest in the

two experiments. Comparison of spring 1991 yields with those of the more thoroughly trimmed lettuce of spring 1992 does suggest, however, that the yields of the latter were greater (Table 3.6). It may be that where yield was potentially less (i.e. in the spring of 1991) it was also less susceptible to reduction by interference from the low density of spiny amaranth. For example, if lettuce growth was limited by light availability, then nutrient uptake by the low weed density may not have been sufficient to result in mineral nutrient availability becoming more limiting to growth than light availability. During the final five weeks prior to harvest of the spring 1991 experiment there was considerable rainfall and substantially reduced solar radiation during two periods of several days. Under field conditions, lettuce yield has been shown to be sensitive to light reductions of as little as 27% of prevailing solar radiation when such shading occurs during head formation (Sanchez et al., 1989). Based on these findings, it was suggested that cloudy weather may be a limiting factor for lettuce yields in south Florida. In the 1992 study, where greater yields were obtained, a resource other than light may have been the yield limiting factor. In this case, spiny amaranth at the low density of the study may have effectively reduced the availability of the factor ultimately limiting lettuce yield, thus resulting in the yield reductions that occurred.

Lettuce Nutrient Analysis

Concentrations of macronutrients in lettuce in the spring 1991, fall 1991 and spring 1992 studies are given in Tables 3.7, 3.8 and 3.9, respectively. Nitrogen concentrations ranged from 1.21% in the 1992 study to 3.5% in the fall of 1991. Greatest yields were obtained in the spring of 1992 (Table 3.6), the study in which lettuce N was lowest (Table 3.9). In the spring 1992 study, fertilizer P application by either of the two methods resulted in a 15% decrease in lettuce N concentrations.

Concentrations of P in lettuce ranged from 0.4 to 1.2 in the studies (Tables 3.7, 3.8 and 3.9). In each of the spring studies (Tables 3.7 and 3.8), P concentrations were greatest with broadcast P application, intermediate with banded P application and lowest when no P fertilizer was applied. In the spring 1991 study there was an interaction between WD and DWI. This interaction is presented in Table 3.10. For the duration of weed interference of 35 days, P concentrations in lettuce were lower under high than low weed density. This suggests that spiny amaranth may have been competing with lettuce for P; the more intense competition under the higher spiny amaranth density resulting in lowered P concentrations in lettuce.

In the spring 1992 study PA interacted with weed density (Table 3.9). The interaction is explored in Table

Table 3.7 The effect of P application, weed density, duration of weed interference and their interactions on macronutrient concentrations in lettuce in the spring 1991 experiment.

Main Effect[a]	N	P	K	Ca	Mg
	Nutrient				
PA	- - - concentration (% of dry wt.) - - -				
None	2.38	0.54a[c]	6.18	1.89	0.45a
Band	2.02	0.79b	5.73	1.78	0.41b
Broadcast	2.08	1.14c	6.33	1.65	0.39b
Signif.[b]	ns	***	ns	ns	**
WD					
Low	2.18	0.83	6.34	1.87	0.43
High	2.16	0.79	5.80	1.69	0.40
Signif.	ns	ns	ns	*	**
DWI					
0	2.27	0.84	5.61	1.73	0.41
7	2.16	0.83	6.39	1.62	0.41
21	2.26	0.78	6.52	1.80	0.42
35	2.12	0.80	6.47	1.97	0.44
49	1.99	0.80	5.46	1.83	0.41
Signif.	ns	ns	ns	ns	ns
Interactions	- - - - level of significance - - - -				
PA x WD	ns	ns	ns	ns	*
PA x DWI	ns	ns	ns	ns	ns
WD x DWI	ns	*	ns	ns	ns
PA x WD x DWI	ns	ns	ns	*	ns

[a]Main effects are P application (PA), weed density (WD) and duration of weed interference (DWI). Low and high weed densities are 1 and 4 plants per 2.3 m of bed, respectively. Durations of weed interference in days after plots established.

[b]Significance of the main effect.

[c]Phosphorus application means within a column followed by a common letter are not significantly different at alpha=0.05 based on Duncan's Multiple Range Test.

Table 3.8 The effect of P application, weed density, duration of weed interference and their interactions on macronutrient concentrations in lettuce in the fall 1991 experiment.

Main Effect[a]	Nutrient				
	N	P	K	Ca	Mg
PA	- - - concentration (% of dry wt.) - - -				
None	3.31	1.12	8.78	1.44	0.36
Band	3.31	1.14	8.34	1.49	0.36
Broadcast	3.50	1.22	8.49	1.48	0.36
Signif.[b]	ns	ns	ns	ns	ns
WD					
Low	3.39	1.16	8.56	1.49	0.36
High	3.36	1.16	8.51	1.45	0.36
Signif.	ns	ns	ns	ns	ns
DWI					
0	3.24	1.17	8.65	1.49	0.35
7	3.48	1.13	8.53	1.44	0.36
17	3.32	1.17	8.52	1.46	0.36
28	3.39	1.20	8.37	1.45	0.36
36	3.44	1.13	8.61	1.5	0.36
Signif.	**	ns	ns	ns	ns
Interactions	- - - - level of significance - - - -				
PA x WD	ns	ns	**	ns	ns
PA x DWI	ns	ns	ns	ns	ns
WD x DWI	ns	ns	ns	ns	ns
PA x WD x DWI	ns	ns	ns	ns	ns

[a]Main effects are P application (PA), weed density (WD) and duration of weed interference (DWI). Low and high weed densities are 1 and 4 plants per 2.3 m of bed, respectively. Durations of weed interference in days after plots established.

[b]Significance of the main effect.

Table 3.9 The effect of P application, weed density, duration of weed interference and their interactions on macronutrient concentrations in lettuce in the spring 1992 experiment.

Main Effect[a]	Nutrient				
	N	P	K	Ca	Mg
PA	- - - concentration (% of dry wt.) - - -				
None	1.44a[c]	0.45a	5.57	2.27a	0.58
Band	1.24b	0.67b	5.50	2.50b	0.61
Broadcast	1.21b	0.80c	5.16	2.59b	0.62
Signif.[b]	*	***	ns	*	ns
WD					
Low	1.29	0.65	5.33	2.47	0.61
High	1.30	0.64	5.49	2.43	0.60
Signif.	ns	ns	ns	ns	ns
DWI					
0	1.37	0.65	5.32	2.39	0.60
6	1.25	0.67	5.65	2.50	0.62
16	1.28	0.61	5.13	2.40	0.59
27	1.34	0.63	5.47	2.48	0.60
36	1.24	0.65	5.49	2.49	0.61
Signif.	ns	ns	ns	ns	ns
Interactions	- - - - - level of significance - - - - - - -				
PA x WD	ns	*	ns	ns	ns
PA x DWI	ns	ns	ns	ns	ns
WD x DWI	ns	ns	ns	ns	ns
PA x WD x DWI	ns	ns	ns	ns	ns

[a]Main effects are P application (PA), weed density (WD) and duration of weed interference (DWI). Low and high weed densities are 1 and 4 plants per 2.3 m of bed, respectively. Durations of weed interference in days after plots established.

[b]Significance of the main effect.

[c]Phosphorus application means within a column followed by a

Table 9--continued.

common letter are not significantly different at alpha=0.05 based on Duncan's Multiple Range Test.

Table 3.10 The interaction between duration of weed interference and spiny amaranth density for phosphorus concentration in lettuce in the spring 1991 experiment.

Duration of weed interference[a]	Spiny amaranth density[b] Low	High
	- P conc. (% of dry wt.) -	
0	0.84a[c]	0.84a
7	0.83a	0.81a
21	0.77a	0.85a
35	0.94a	0.72b
49	0.83a	0.78a

[a]Duration of weed interference in days after plot establishment.

[b]Low and high densities are 1 and 4 plants per 2.3 m of bed, respectively.

[c]Values within a row followed by the same letter are not different based on paired means comparisons at alpha = 0.05.

Table 3.11 The interaction between phosphorus fertilizer application and spiny amaranth density for phosphorus concentration in lettuce in the spring 1992 experiment.

Phosphorus application	Spiny amaranth density[a] Low	High	Within row comparisons[b]
	- P conc. (% of dry wt.) -		
None	0.46a[c]	0.44a	ns
Band	0.65b	0.69b	ns
Broadcast	0.82c	0.77c	ns

[a]Low and high densities are 1 and 4 plants per 2.3 m of bed, respectively.

[b]Differences are significant based on paired means comparisons.

[c]Values within a column followed by the same letter are not different based on paired means comparisons at alpha = 0.05.

3.11. Phosphorus concentrations in lettuce under each of low and high weed densities were lowest where no P was applied, intermediate with banded P and greatest with broadcast P. The source of the interaction, however, was not detected. There were not, therefore, any consistent interactions between the P fertilizer treatments and the other experimental factors for P concentrations in lettuce in the spring 1991 and 1992 experiments, the two in which yields were effected in a similar manner in the two experiments.

In the fall experiment, the high P concentrations in lettuce for which no fertilizer P was added were unexpected (Table 3.8). Even though lettuce P concentration at maturity was not found to be affected by P application, lettuce yields did show a response to applied P fertilizer (Table 3.6), as was previously discussed. Lettuce leaf samples were collected at midseason from plants in the weed-free plots of this experiment. Phosphorus concentration data for these leaf samples are given in Table 3.12. These data indicate that P concentration in lettuce leaves did show a response to fertilizer P application. Sanchez et al. (1990) found that, on occasion, good lettuce yields are obtained when soil P status is below that which would normally be required. They attributed this to a combination of weather conditions being optimal for efficient P use by the plant and to movement of P into the root as soil water

Table 3.12 Phosphorus concentrations in outermost intact lettuce leaves of weed-free lettuce at mid-season in the fall 1991 experiment.

Phosphorus Application	Phosphorus Concentration
	- - - % of dry weight - - -
None	0.21a[a]
Banded	0.39b
Broadcast	0.49c

[a]Values followed by the same letter are not different based on Duncan's multiple range test at alpha=0.05.

moved upwards under conditions of high evapotranspiration. It may be that such a situation occurred during the latter stages of crop development, resulting in the high P concentrations found at maturity. Yield differences for the P application treatments would therefore have occurred as a result of the nutritional status that prevailed early in the season, when a response to P was evident. The finding that 70% of the total nutrient uptake by a crisphead lettuce crop can occur during the last three weeks prior to harvest (Zink and Yamaguchi, 1962) favors the plausibility of this explanation.

Potassium concentrations across experiments ranged from 5% in the spring 1992 study to greater than 8% in the fall of 1991 (Tables 3.7, 3.8 and 3.9). In the spring 1991 and 1992 experiments, K was not found to be influenced by the experimental factors (Tables 3.7 and 3.9). The interaction between PA and WD in the fall 1991 experiment (Table 3.8) did not appear to be meaningful.

Calcium concentrations in lettuce ranged from as low as 1.44% in the fall 1991 study (Table 3.8) to as high as 2.5% in the spring 1992 study (Table 3.9). There did not appear to be any meaningful trends for Ca concentration response to P application.

Magnesium concentrations ranged from 0.36% in the fall study (Table 3.8) to 0.6% in the spring 1992 experiment (Table 3.9). There did not appear to be any meaningful

interactions between the experimental factors for Mg concentrations.

Nutrient concentrations in lettuce were influenced more often by fertilizer P application than by weed density or duration of weed interference. For each of N, P and Ca, P application influenced the concentrations of the nutrient in lettuce in at least one experiment. The most pronounced effect of P application was on lettuce P concentrations. This P concentration response to fertilizer P application by lettuce somewhat parallelled the response of lettuce yields to P application, as previously discussed, for the two spring studies. There was, however, some difference in how yields and lettuce P concentrations responded to the application method. For the broadcast application of fertilizer P, lettuce P concentrations were greater than in the case of the band application for each of the spring studies. In each of these experiments, yields were essentially not found to differ for the band and broadcast fertilizer P application (Figures 3.1 and 3.2). This suggests that with broadcast fertilizer application lettuce may have been taking up more P than was required for the yields obtained in the experiments.

Lettuce yields in the spring studies were influenced by interactions between WD and DWI (Table 3.6). There was little indication, however, of interactions between WD and DWI for P concentrations in lettuce. The only reduction in

P concentration due to increased weed density was for the 35 day duration of weed interference in the spring 1991 experiment. It does not appear that interactions between these experimental factors were of underlying importance to the P nutrition of lettuce as measured by nutrient concentrations in the crop at maturity.

Although the crop was affected by spiny amaranth interference, the immediate cause of yield loss to the weed does not appear to be due to interference with the P nutrition of the crop. Phosphorus nutrition has been implicated as a factor which can influence the outcome of intraspecific competition in plants (Buckeridge and Norrington-Davies, 1986; Chapin and Bieleski, 1982). In these studies with lettuce and spiny amaranth, however, essentially only the growth of lettuce was found to be influenced by P fertility. Competition between lettuce and spiny amaranth was influenced by P nutrition only in the sense that it was a determinate factor for lettuce growth.

Although spiny amaranth interference reduced lettuce yields in each of the spring studies, these yield reductions do not appear to have been due to the reduction of P availability to lettuce, as measured by P concentrations at maturity. However, the fact that some reduction in lettuce P concentrations did occur due to increased weed density suggests that there may have been some interaction between spiny amaranth and the P nutrition of lettuce. The

nutritional data was obtained for lettuce in these studies at maturity. This data, therefore, does not provide direct indication of the nutritional status of the crop during the entire period during which competition between it and the weed occurred. Nutritional status while competition is occurring, rather than after it has occurred, can be of greater value in assessing the importance of mineral nutrition on competition (Glauninger and Holzner, 1982).

Spiny Amaranth Nutrient Analysis

Macronutrient concentrations in spiny amaranth for the spring 1991, fall 1991 and spring 1992 experiments are given in Tables 3.13, 3.14 and 3.15, respectively. In the spring of 1992, N concentrations were influenced by duration of weed interference (Table 3.16), which is a measure of plant age. In the fall of 1991, duration of weed interference affected N concentrations in amaranth (Table 3.14). The interactions between the experimental factors for N concentrations did not appear to be meaningful.

Phosphorus concentrations in the fall 1991 study were influenced by duration of weed interference but not the other experimental factors (Table 3.14). In the spring 1991 study there was an interaction between density and duration of weed interference (Table 3.13), which is explored in Table 3.16. At the final duration of weed interference, P concentration was lower for the high than the low density.

Table 3.13 The effect of P application, weed density, duration of weed interference and their interactions on macronutrient concentrations in spiny amaranth in the spring 1991 experiment.

Main Effect[a]	N	P	K	Ca	Mg
PA	- - - concentration (% of dry wt.) - - -				
None	3.51	0.60a[c]	7.03	2.81a	0.80a
Band	3.26	0.69b	6.80	2.65b	0.73b
Broadcast	3.23	0.80c	7.00	2.68b	0.70b
Signif.[b]	ns	**	ns	*	*
WD					
Low	3.38	0.69	6.85	2.72	0.75
High	3.29	0.71	7.04	2.70	0.74
Signif.	ns	ns	ns	ns	ns
DWI					
7	4.64	0.88	5.04	3.32	0.99
35	3.10	0.80	9.47	2.98	0.78
49	2.26	0.43	6.43	1.84	0.46
Signif.	***	***	***	***	***
Interactions	- - - - level of significance - - - -				
PA x WD	**	ns	ns	ns	ns
PA x DWI	***	ns	***	ns	ns
WD x DWI	ns	*	**	*	ns
PA x WD x DWI	ns	ns	**	ns	*

[a]Main effects are P application (PA), weed density (WD) and duration of weed interference (DWI). Low and high weed densities are 1 and 4 plants per 2.3 m of bed, respectively. Durations of weed interference in days after plots established.

[b]Significance of the main effect.

[c]Phosphorus application means within a column followed by a common letter are not significantly different at alpha=0.05 based on Duncan's Multiple Range Test.

Table 3.14 The effect of P application, weed density, duration of weed interference and their interactions on macronutrient concentrations in spiny amaranth in the fall 1991 experiment.

Main Effect[a]	Nutrient				
	N	P	K	Ca	Mg
PA	- - - concentration (% of dry wt.) - - -				
None	2.24a[c]	0.96	6.45	3.15	0.83
Band	2.32a	0.97	6.00	3.27	0.79
Broadcast	2.23a	1.07	6.20	3.27	0.75
Signif.[b]	*	ns	ns	ns	ns
WD					
Low	2.18	0.98	6.29	3.19	0.78
High	2.34	1.02	6.16	3.28	0.80
Signif.	ns	ns	ns	ns	ns
DWI					
7	4.02	0.91	4.90	2.89	0.85
17	1.92	0.86	6.04	3.75	0.83
28	1.69	1.11	6.65	3.86	0.74
36	1.71	1.12	7.09	2.38	0.75
Signif.	***	***	***	***	***
Interactions	- - - - level of significance - - - -				
PA x WD	ns	ns	ns	ns	ns
PA x DWI	**	ns	ns	ns	ns
WD x DWI	ns	ns	ns	ns	ns
PA x WD x DWI	ns	ns	ns	ns	ns

[a]Main effects are P application (PA), weed density (WD) and duration of weed interference (DWI). Low and high weed densities are 1 and 4 plants per 2.3 m of bed, respectively. Durations of weed interference in days after plots established.

[b]Significance of the main effect.

[c]Phosphorus application means within a column followed by a common letter are not significantly different at alpha=0.05 based on Duncan's Multiple Range Test.

Table 3.15 The effect of P application, weed density, duration of weed interference and their interactions on macronutrient concentrations in spiny amaranth in the spring 1992 experiment.

Main Effect[a]	Nutrient N	P	K	Ca	Mg
	- - - concentration (% of dry wt.) - - -				
PA					
None	2.64	0.65	5.83	3.92	0.82
Band	2.86	0.65	5.66	3.87	0.82
Broadcast	2.92	0.68	5.33	3.86	0.84
Signif.[b]	ns	ns	ns	ns	ns
WD					
Low	2.83	0.67	5.66	3.93	0.83
High	2.79	0.66	5.55	3.84	0.83
Signif.	ns	ns	ns	ns	ns
DWI					
6	4.77	0.87	4.56	4.89	0.86
16	1.47	0.78	5.70	3.61	0.96
27	3.20	0.57	6.17	3.72	0.81
36	1.79	0.42	5.98	3.32	0.69
Signif.	***	***	***	***	***
Interactions	- - - - level of significance - - - -				
PA x WD	ns	ns	ns	ns	ns
PA x DWI	ns	***	**	ns	**
WD x DWI	ns	ns	ns	ns	ns
PA x WD x DWI	ns	ns	ns	ns	ns

[a]Main effects are P application (PA), weed density (WD) and duration of weed interference (DWI). Low and high weed densities are 1 and 4 plants per 2.3 m of bed, respectively. Durations of weed interference in days after plots established.

[b]Significance of the main effect.

Table 3.16 The interaction between duration of weed interference and spiny amaranth density for phosphorus concentration in spiny amaranth in the spring 1991 experiment.

Duration of weed interference[a]	Spiny amaranth density[b]	
	Low	High
	- P conc. (% of dry wt.) -	
7	0.86a[c]	0.90a
35	0.76a	0.83a
49	0.45a	0.40b

[a]Duration of weed interference in days after plot establishment.

[b]Low and high densities are 1 and 4 plants per 2.3 m of bed, respectively.

[c]Values within a row followed by the same letter are not different based on paired means comparisons at alpha = 0.05.

In this experiment there was also a response to P application (Table 3.13). Fertilizer P application resulted in higher spiny amaranth P concentrations, which were also greater with the broadcast than the band application. Spiny amaranth biomass showed a positive response to P application (Table 3.3), however, biomass was not differentially influenced by the P application method. It thus appears that, in the case of the broadcast treatment, amaranth took up more P than was needed for the biomass accumulation that occurred in these studies. In the spring 1992 experiment there was an interaction between P application and duration of weed interference (Table 3.15), which is explored in Table 3.17. For the duration of weed interference of 6 days, P concentrations were found to be greater for the broadcast applied P than for the other treatments. Spiny amaranth biomass, however, did not show a differential response to the P application treatments for this duration of weed interference (Table 3.5). Thus, P concentration in spiny amaranth does not appear to have been a limiting factor to growth of the plant, as reflected by biomass, in these studies.

In the fall 1991 experiment, K concentrations in spiny amaranth were influenced by duration of weed interference but not the other experimental factors (Table 3.14). The interactions between the experimental factors for K concentration did not appear to be meaningful.

Table 3.17 The interaction between duration of weed interference and phosphorus application for phosphorus concentration in spiny amaranth in the spring 1992 experiment.

Duration of weed interference[a]	Phosphorus application		
	None	Band	Broadcast
	- - P conc. (% of dry wt.)- -		
6	0.74a[b]	0.86a	1.03b
16	0.76a	0.75a	0.84a
27	0.64a	0.57a	0.52a
36	0.48a	0.40a	0.39a

[a]Duration of weed interference in days after plot establishment.

[b]Values within a row followed by the same letter are not different based on paired means comparisons at alpha = 0.05.

In the fall of 1991 (Table 3.14) and the spring of 1992 (Table 3.15) Ca concentrations were only influenced by duration of weed interference. The interaction in the spring 1991 study did not appear to be meaningful. In the spring 1991 experiment Ca concentrations showed a negative response to P application but did not differ for the two P application methods (Table 3.13).

In the fall 1991 experiment Mg concentrations showed a response to duration of weed interference but not to the other experimental factors (Table 3.14). Interactions between the experimental factors for Mg concentrations did not appear to be meaningful.

The predominate factor which influenced nutrient concentrations in spiny amaranth was duration of weed interference. Mineral nutrient concentrations in plants are controlled by genetic uptake potential of the plant, nutrient availability in the growing medium and plant age (Mengel and Kirkby, 1987). Plant age was increasing with DWI and therefore may have been a factor influencing the nutrient concentrations found in amaranth. Nutrient availability of muck soils varies with field conditions (Lucas, 1982). Rainfall, for example, can leach nitrate N out of the root zone. The effects of time, therefore, may be due to a combination of several factors.

Spiny amaranth biomass was influenced by density. However, nutrient concentrations do not appear to have been

the underlying cause of this affect. Foliage of adjacent plants at low density never overlapped but foliage did overlap extensively for plants at the high density. This suggests that interference for light between plants may have been a factor involved in the biomass responses to density.

The effect of spiny amaranth on lettuce yields was dependent on growth of the weed. Lettuce yields were not affected by the relatively low weed biomass of the fall 1991 experiment. In the spring experiments, where substantially greater weed biomass was achieved, lettuce yields were reduced as the duration of weed interference was extended (Figures 3.3, 3.4 and 3.5).

Lettuce yields were also influenced by fertilization such that application by either method resulted in yield increases of approximately 100 percent. Spiny amaranth biomass, on the other hand, was only marginally influenced by P fertilization. There was also some indication that broadcast P application resulted in lettuce being more susceptible to weed interference than did band application (Figures 3.1 and 3.2). Lettuce yields in the absence of weed interference were slightly greater when P was applied broadcast than when banded. The more pronounced effect of weed interference on lettuce where P was applied broadcast suggests that lettuce susceptibility to weed interference is greatest where yield is potentially greatest. This effect did not seem to be due to the nutritional status of the

crop. Nutrient concentrations in lettuce were not found to be differentially influenced by weed interference in any meaningful fashion.

This study corroborates the findings of Sanchez et al. (1990) that band application of P is a viable alternative to broadcast application for lettuce production on south Florida histosols. However, the yield differences obtained in weed-free lettuce for band versus broadcast application suggests that the latter method was slightly superior in the current study. These differences occurred regardless of whether one half or one third of the broadcast rate was used in the band application and, therefore, may be due to more than optimization of rate. These results suggest that further study of fertilizer P placement is needed.

Spiny amaranth interference with lettuce was not found to be dependent on P fertilization to any great extent. While lettuce growth was dependent on P fertilization, this was not found to be the case for spiny amaranth. Spiny amaranth generally grew as well with or without the addition of P fertilizer. Thus, any changes in the competitive interactions between lettuce and spiny amaranth due to P fertilization would be due to responses by the crop, but not the weed, to P fertility. Because spiny amaranth grows well at low P, it could be expected to be a good competitor under conditions of low P. In light of the findings of these studies, in order to avoid crop loss to competition by spiny

amaranth, growers will need to continue to exercise the same weed control practices when using a banded P application system as with the currently used broadcast technique.

CHAPTER 4
SPINY AMARANTH (*Amaranthus spinosus* L.) COMPETITION WITH LETTUCE (*Lactuca sativa* L.) AS INFLUENCED BY PHOSPHORUS FERTILITY OF MUCK SOIL

Introduction

Weed management in lettuce (*Lactuca sativa* L.) produced on histosols in Florida is highly dependent on control measures applied after weeds emerge, consequently resulting in intermittent weed presence in the crop. This is especially so during the first several weeks of crop growth since weed control measures are generally not initiated until 3 weeks after planting, the time at which the crop is thinned to the desired stand and weeds are removed. Studies concerned with how the duration of weed presence affects lettuce have been reported. Field studies in England showed that weed densities of 65 per m^2 resulted in complete loss of marketable yield when weeds were allowed to remain present in the crop (Roberts et al., 1977). Weed populations in these studies were comprised of a mixture of gramineous and dicotyledonous species. These studies showed that elimination of weeds by hand at 3 weeks after emergence of the crop, with no additional weed removal, was sufficient to prevent yield loss. The effect of early season

interference with crisphead lettuce by specific weed species has also been assessed (Shrefler et al., 1991). Livid amaranth (Amaranthus lividus L.) at 120 plants per m^2 did not affect marketable lettuce yield when removed at 19 days after planting of the crop. Delaying weed removal an additional 15 days resulted in the complete loss of marketable yield. Common purslane (Portulaca oleracea L.) at 15 plants per m^2 resulted in a reduction in the quantity of marketable lettuce heads as weed removal was delayed from 16 to 37 days after planting of the crop (Shrefler et al., 1991). Weed interference during this 21 day period resulted in a 36% yield decrease, which occurred in a linear fashion with time.

Lettuce production on histosols also requires careful management of soil fertility (Sanchez, 1990; Lucas, 1982). The crop responds to each of P and K amendment in a predictable manner on these soils (Sanchez and Burdine, 1988). Critical concentrations in lettuce tissue have been established for these nutrients (Sanchez et al., 1988). While K fertilizer can be applied as needed after the crop is planted, the entire amount of P to be used for a crop is applied before planting. This P application has traditionally been made by broadcasting the fertilizer uniformly over the field and incorporating it into the soil prior to planting. It has been shown, however, that when fertilizer P is applied in a band below the crop row,

optimum yields can be obtained with substantially reduced rates of P fertilizer on a field basis (Sanchez et al., 1990). It was also found that concentrations of available P in the crop root zone at 30 days after application were greater in the case of the band method than the broadcast method. Weed and crop interactions during early growth would therefore be occurring under different P availability conditions for these two fertilizer application methods.

Lettuce is particularly sensitive to phosphorus supply during early growth. This was demonstrated in greenhouse experiments where P was applied simultaneously by 2 methods (Costigan, 1984). One method was to thoroughly mix dry, granulated triple superphosphate with the soil. The highest rates used were adequate to give optimal yields when this was the only source of P fertilization. Pregerminated lettuce seed were sown into, and covered with, this soil. The second source of P was a solution of $NH_4H_2PO_4$ which was applied to the seeding zone of the soil. By 21 days after planting, lettuce dry weight had responded positively to the increased rate of P supplied as a solution but not to P applied dry to the soil.

Phosphorus status has also been shown to influence the capacity of lettuce seedlings to respond to other nutrients (Costigan and Heaviside, 1988). In these studies, starter solutions of varied nutrient concentrations were compared for use with lettuce transplants. As P concentration in

lettuce tissue increased from 0.3 to 0.6 %, the growth response of lettuce to the various starter solutions increased in a linear fashion. Thus, P availability was the ultimate factor limiting plant growth.

In another study the effect of interruptions in the supplies of N, P and K to lettuce during early growth following transplanting was assessed (Burns, 1987). Plants were grown in sand culture to which nutrient solutions were supplied. The effects of deprivation of each of N, P and K were tested by withholding the individual nutrients, beginning at the time of transplant, for several durations. Shoot growth rates decreased within 2 and 6 days after withholding the nutrients N and K, respectively, but not until 9 days in the case of P. Restoration of the supply of each of the nutrients resulted in a rapid increase in plant growth rate. Their data also suggest that growth rate sensitivity to withholding N and K was not as great as for P deprivation, which resulted in abrupt cessation of growth once the nutrient was withheld for 9 days.

Interactions between weeds and crop plants are found to be mediated by the availability of resources consumed during plant growth (e.g. water and nutrients) (Aldrich, 1987; Radosevich and Holt, 1984), non-consumable conditions that influence growth (e.g. temperature) and allelopathic responses (Radosevich and Holt, 1984). Competition refers to situations in which the growth of plants interacting with

one another is limited due to consumable resources being quantitatively inadequate (Goldberg, 1990; Radosevich and Holt, 1984). In the case of nutrients as the resource for which competition occurs, there are two characteristics which may influence the competitive ability of plants (Goldberg, 1990). One of these is the capability of rapid depletion of the resource in question. The other is the ability to grow at depleted resource levels.

Plant competition studies provide a means of evaluating the effects that certain management practices have on weed and crop interactions (Conolly, 1988). A technique for the study of nutrients as limiting factors of plant growth under interspecific competition was established by Hall (1974a) and has been applied for several nutrients and several plant mixtures (Bhaskar and Vyas, 1988; Hall, 1974a; Hall, 1974b). The approach utilizes the replacement series method. Monocultures of each of two species are established along with mixtures of the two species at varied proportions. Overall density is held constant for the series. While the replacement series technique is generally applied to biomass or yield, Hall's approach is to also look at nutrient content in plant tissue. By including varied fertility as a factor, the results give an indication of how component plants of the mixture fare in extracting the nutrient in the presence of the other species. Using this approach, Hall (1974b) was able to conclude that the grass component of a

grass-legume mixture competed more successfully than the legume for K. Bhaskar and Vyas (1986) applied the technique to a wheat (Triticum aestivum L.) and common lambsquarters (Chenopodium album L.) mixture. They found that competitive interference occurred for P (with common lambsquarters being more aggressive), and to a lesser extent for N (in which case wheat was more aggressive).

Wilson (1988) tabulated findings of studies testing the effects of nutrient addition to plant mixtures in which plant interaction was limited to that which would occur below ground. Several indices of competition were utilized, depending on the nature of the original study, to assess the effect of nutrient addition on competition. Competition was found to increase as often as it decreased, leading Wilson to conclude that there is "no case for using the concept of reduced competition effects at higher resource levels in the interpretation of ecological processes or experimental results". It appears that the influence of nutrient addition on plant competition must be considered on a case by case basis rather than broad generalization.

Nevertheless, it has been demonstrated that nutrients can be important in influencing the outcome of interspecific plant competition in agricultural settings (Hall, 1974b; Siddiqi et al., 1985; Shribbs, 1986; Weiner, 1980). In these studies, competition is found to be dependent on amounts of nutrients supplied to plants grown in mixture.

The influence of one nutrient on competition may also be dependent on the status of other nutrients. In studies with red clover (Trifolium incarnatum L.) and Italian ryegrass (Lolium multiflorum Lam.) the effect of combined P and K addition under low N fertility was examined using replacement methods (Weiner, 1980). Red clover was more sensitive to intraspecific competition than it was to interspecific competition with ryegrass. These competitive interactions were differentially influenced by soil fertility in several ways. In portions of the study conducted at low N, ryegrass negatively affected red clover at low P and K fertility but not when P and K levels were increased. When N was added along with P and K, ryegrass became dominant over the legume.

Glauninger and Holzner (1982) discussed why competition for nutrients is not estimable by simply looking at nutrient levels in plants. Recognizing that crops can suffer severely due to nutrient uptake by weeds, these authors are of the opinion that more important than absolute uptake of nutrients by competitors are the relations between nutrient availability and the needs of the crop. Interpretation of altered nutrient status of crops due to weed competition is probably dependent on the nature of competition. In studies with bell peppers, increased weed "cover" resulted in decreased pepper foliage Fe while B, Cu, P and K were increased (Frank et al., 1988). These increases may be the

result of reduced plant growth due to others factors becoming limiting rather than an increase in nutrient uptake. Reduced growth has a concentrating effect on nutrients (Mengel and Kirkby, 1987).

Additional reasoning for nutrient levels in plants being of limited value as an indicator of competition for nutrients is that the roots of weeds and crops in mixture may vary in the region of the soil profile they inhabit, and thus not be drawing totally on the same nutrient pool. A study by Chambers and Holm (1965) using P^{32} to study the site of P uptake from soil by green foxtail (Setaria viridis (L.) Beauv.), redroot pigweed (Amaranthus retroflexus L.) and common bean (Phaseolus vulgarus L.) demonstrated this effect. Common bean received 60% of its P from within a 7.5 cm radius around itself, to a depth of 7.5 cm, while redroot pigweed absorbed 60% of its P at the 15 cm depth of a 15 cm radius. Localized nutrient supply can have a strong stimulatory effect on root proliferation in the vicinity of the nutrient (Anghinoni and Barber, 1980; Drew, 1978; Mengel and Kirkby, 1987). The possibility of such a response should be kept in mind in studying fertility effects on plants growing in mixture when nutrient additions are made to the rooting media.

Studies on nutrients as limiting factors for which plants compete have most often considered N although any nutrient could conceivably be important in this context

(Zimdahl, 1980). Several studies provide evidence for the occurrence of competition for nutrients other than N between roots (Caldwell et al., 1987; Kranz and Jacob, 1977). Caldwell et al. (1987) demonstrated that plants whose roots shared a mutual soil location were drawing on a common pool of P. This was shown by measuring uptake of dual isotopes of P. Defoliation of one of the species of the mixture, which would reduce its nutrient uptake, resulted in an immediate increase in P uptake by the other species.

Competition for P was studied in mixtures of flax (Linum usitatissimum L.) and large seeded falseflax (Camelina sativa (L.) Crantz) by monitoring the uptake of P^{32} over time by both species (Kranz and Jacob, 1977). When grown in mixture, uptake of P by flax was slower than when grown in monoculture. Falseflax uptake of P, conversely, was greater in mixture than in monoculture. Falseflax thus competed more strongly for P than flax, both interspecifically and intraspecifically.

The occurrence of competition between roots for resources is dependent on the overlap of soil depletion shells of adjacent roots (Fusseder et al., 1988). A model for the determination of root overlap and the effect of nutrient uptake on soil P status in the root zone was applied to field studies with maize. These studies demonstrated that competition for P was nearly non existent in this case. This was because soil P in the root

microenvironment was not altered by P uptake for a distance greater than 1 mm away from the root.

Changes in competitive interactions between plants as nutrient availability is modified could conceivably be dependent on the relative responsiveness of the components of the mixture (Hoveland et al., 1976; Weiner, 1980) as well as on the existence of an actual nutrient competition phenomena (Hall, 1974b; Weiner, 1980). The fact that a mixture responds to nutrient availability, however, does not indicate that the nature of competition within the mixture will necessarily be influenced by alteration of nutrient levels (Buckeridge and Norrington-Davies, 1986).

Increases in nutrient availability in competitive situations can be more detrimental than advantageous to the crop in some instances. In response to a proposal that weed competition for nutrients could be compensated for by increased fertilization, Alkamper (1976) reviewed literature on the influence that fertilization has on crops and weeds and the control of weed infestations. It was concluded that fertilizing to reduce crop loss to weeds is not feasible, except in the case of low weed densities. The reasons for this are that weeds may grow faster than crops and absorb nutrients more rapidly, that weeds are more responsive to nutrients than crops in some cases and that fertilization of weeds may only hasten the onset of crop loss due to weeds. The study also suggested that proper timing of

fertilization, in conjunction with weed control, can be valuable in enhancing the ability of the crop to suppress weeds that survive control measures.

Weedy species vary in response to differences in soil fertility. Some grow well at low levels of available nutrients while phenotypic plasticity of others allows them to take advantage of high fertility by growing luxuriously (Glauninger and Holzner, 1982). Plants in the family Chenopodiaceae respond so to high nitrate availability. Redroot pigweed has been found to respond to P more so than several other warm season weeds (Hoveland et al., 1976), and exhibit P accumulation seven times that of beans (Zimdahl, 1980). Hoveland et al. (1976) cite that species of the genera Amaranthus, Chenopodium and Portulaca are particularly efficient in K uptake and that the presence and growth of lambsquarters has been considered an indicator of P deficiency in soil.

Nutrient addition can indeed modify the competitive interactions in plant mixtures (Hall, 1974b; Siddiqi et al., 1985; Shribbs, 1986; Weiner, 1980). Hall (1974b) studied the influence of added K on competition between Nandi setaria (Setaria anceps cv. Nandi) and Greenleaf desmodium (Desmodium intortum cv. Greenleaf). At low K, desmodium growth was greatly suppressed by setaria when the latter comprised only 25% of the mixture. With added K, however,

desmodium growth was only marginally suppressed by setaria. Setaria growth was not greatly influenced by added K.

The potential for nutrient addition to influence competitive relations between plants can be not only species dependent but also, for crops, cultivar dependent (Siddiqi et al., 1985). The competitive ability between barley (Hordeum vugare L.) cultivars and wild oat (Avena fatua L.) at varied K fertility was studied. Some cultivars were competitive at high and low K, others at high K only and still others were only weakly competitive at even high K.

The influence of ground cover species on apple (Malus pumila Miller) seedlings was studied by Shribbs et al. (1986). Leaves of apples grown with groundcover were found to have reduced N levels. Addition of N overcame the effect only partially.

The overall objective of studies reported here was to assess the competitive interactions under varied P regimes between lettuce and spiny amaranth (Amaranthus spinosus L.) during early growth. The replacement series design is useful for exploring the way in which two species interact (Cousens, 1991). The outcome of studies utilizing this approach is found to be influenced by the density at which experiments are conducted (Rejmanek et al., 1989). As density is increased, indices that quantify competition in replacement series tend to become less density dependent (Cousens, 1991). Replacement studies should therefore be

conducted so that constant final yields are achieved (Radosevich, 1987). This can be accomplished by the selection of a suitable combination of density and experiment duration.

In order to obtain constant final yield of lettuce during early growth, densities substantially higher than what would be practical in culture of the crop would be required (suggested by data of Paul and Ayres, 1987). A modified application of the replacement series which enables assessment of competition over a range of densities was proposed by Jolliffe et al. (1984). It was applied to studies on competition between groundsel (*Senecio vulgaris* L.) and lettuce (Paul and Ayres, 1987). Using this technique, intraspecific and interspecific competition effects can be quantified (Jolliffe et al., 1984; Roush et al., 1989). Experiments in this study were therefore designed so that competition between lettuce and spiny amaranth grown under varied P regimes could be assessed using both replacement series analysis techniques (Conolly, 1986; DeWit and Van Den Bergh, 1965; Rejmanek et al., 1989) and the techniques of Jolliffe et al. (1984).

Materials and Methods

Preliminary Studies

Studies were conducted at Gainesville, Florida to determine how the growth of lettuce 'Southbay' and spiny

amaranth would respond to amendment of soil with phosphorus fertilizer when grown in monoculture under greenhouse conditions. The purpose of these studies was to establish P fertility rates to be used in the competition studies. Soil used was a Pahokee muck {Euic hyperthermic Lithic Medisaprists (Soil Survey Staff, 1978)} which was obtained at the Everglades Research and Education Center (EREC) at Belle Glade, Florida. Soil used in these studies was of low P status (soil test value of 1-3 using the water extractable P analysis) based on EREC soil test procedures (Sanchez, 1990) and had pH values which ranged from 6 to 6.6. Three experiments were conducted in which $Ca(H_2PO_4)_2$ (CP) was applied to soils at the rates indicated in Table 4.1. Prior to CP addition, soil was fumigated in steel drums with methyl bromide, allowed to aerate for at least 3 weeks, and then sieved through a 1 cm mesh galvanized screen. Soil was amended by measuring the amounts of soil and CP to be used, mixing the CP thoroughly with approximately 300 ml of the soil, and then mixing the initial mixture with the remainder of the soil. Pots in which plants were grown were plastic containers, measuring 12 cm in diameter and 21 cm deep and having 4 holes of 0.5 cm diameter in the bottom for drainage. A 1.5 cm layer of Perlite was placed in the bottom of the pots. All of the pots of a given CP rate (for a given experiment) were placed side by side and filled simultaneously with soil to insure homogeneity. After the

Table 4.1 Calcium phosphate soil amendment rates, planting densities and species used in the preliminary experiments.

Experiment	Calcium Phosphate Rate[a]	Densities (plants pot^{-1})	Species[b] Lettuce	Amaranth
Preliminary 1	0, 2, 4 and 8	4, 8, 16 and 32	+	+
Preliminary 2	0, 4, 8, 12 and 16	4	+	+
Preliminary 3	0, 8, 12, 16, 20 and 24	4	+	-

[a]Calcium phosphate rates are equivalent to 0.18 g calcium phosphate per L soil for a rate of 1.

[b]Each species planted separately. Plus (+) sign indicates that the species was used.

pots were filled a straight edge was used to level the soil surface. Pots were then firmly tapped on the floor 4 times to settle the soil. Using the same procedure as in the initial filling, additional soil was added to again fill the pots. The levelling and tapping procedures were then repeated. In final preparation for planting, 200-300 ml of deionized water was slowly added to moisten the soil. In experiment 1 plantings were established at the densities given in Table 4.1. Preliminaries 2 and 3 were limited to a single density (Table 4.1). Preliminaries 1 and 2 consisted of separate sets of treatments for each of lettuce and spiny amaranth while only lettuce was used in preliminary three (Table 4.1). Seed of lettuce and spiny amaranth (collected at the EREC) were sown so that an even spacing between seeds was maintained. Seed placement was confined to the region between 1 and 4 cm away from the pot wall. To insure a complete stand, seed were sown in excess and thinned after emergence. Seed were then covered with a 1 cm layer of vermiculite. Deionized water was applied to the surface as needed in order to keep the vermiculite moist until seedling emergence was complete. At 5 to 10 days after emergence, plants were thinned to achieve the final density. Once densities were established, soil was kept moist by adding nutrient solution containing the micro and macro nutrients needed for plant growth except P (Ross, 1974). These were applied 1 to 3 times weekly. The concentration of Mn was

doubled to insure against deficiency (C. A. Sanchez, personal communication). As plant growth progressed and pot weight differences became evident, container weight differences due to differential moisture loss were compensated for by adding deionized water.

Once densities were established, and before foliage extended beyond the confines of the pot walls, screen cylinders were placed around the pots to confine the foliage. Cylinders used in Preliminary 1 were constructed of window screen. Otherwise cylinders were constructed of hexagonal wire mesh with 2.5 cm openings. These extended to 30 cm above the pot surface.

Preliminary 1 was conducted in a fiberglass greenhouse during February and March of 1991. Preliminaries 2 and 3 were conducted in an air-conditioned glasshouse during June and July of 1991. Preliminaries 1, 2 and 3 were harvested 25, 24 and 27 days, respectively, after 50% seedling emergence had occurred. Shoots were excised at the soil surface, counted, dried at 60 C and weighed.

Competition studies.

Three experiments were conducted to determine the effect of P fertility on competition between lettuce and spiny amaranth during the first 4 weeks of growth following seedling emergence. The studies were conducted in air-conditioned glasshouses, the first during August and

September of 1991 at Gainesville, Florida, the second in March of 1992 (spring) at Belle Glade, Florida and the third in September of 1992 (fall) at Belle Glade. Plant culture methods were essentially the same as those described for the preliminary studies. The density, composition and fertility treatments used in these experiments are given in Table 4.2. In the Gainesville experiment, in addition to the treatments listed in Table 4.2, there were also monocultures of 4 plants per pot for which no CP was added to the soil. This treatment was included for each species in order to show the overall response to CP under the conditions of the study. The Belle Glade experiments differed from the Gainesville one in that a density of 32 plants was included and that the CP rates were modified (Table 4.2). For the spring Belle Glade experiment, in addition to the CP rates listed in Table 4.2, there were additional CP rates of 0, 10.5, 20.5 and 25.5. The only plant densities and compositions grown at these additional CP rates were monocultures of 4 plants per pot. These treatments were included for each species in order to show the overall response to CP under the conditions of the study. Each experiment was conducted as a randomized complete block design with 3 replications. Harvest involved excising shoots just above the soil surface. Excised shoots were counted and then dried and stored at 60 C. Dry weights were obtained and entire shoots were analyzed for mineral nutrients and N. Weed and lettuce

Table 4.2 Calcium phosphate soil amendment rates and planting densities used in the competition experiments.

Experiment	Calcium Phosphate Rate[a]	Densities	
		monoculture[b]	mixture[c]
		- - - - plants pot^{-1} - - - -	
Gainesville	1.5, 7.5 and 13.5	1, 2, 4, 8 and 16	2, 4, 8 and 16
Belle Glade - spring	0.5, 5.5 and 15.5	1, 2, 4, 8, 16 and 32	2, 4, 8, 16 and 32
Belle Glade - fall	0.5, 5.5 and 15.5	1, 2, 4, 8, 16 and 32	2, 4, 8, 16 and 32

[a]Calcium phosphate rates are equivalent to 0.18 g calcium phosphate per L soil for a rate of 1.

[b]Monocultures established for each of spiny amaranth and lettuce.

[c]All mixtures at a 1:1 ratio of spiny amaranth and lettuce.

samples to be used for nutrient analysis were ground in a stainless steel outfitted laboratory mill to pass through a 1 mm mesh sieve. Samples were thoroughly mixed following grinding and a subsample of the ground material was used for analysis. Subsamples were wet ashed as described by Wolf (1982). Nitrogen was determined by a micro-Kjeldahl method (Bremner and Mulvaney, 1982), P was determined colormetrically and K, Ca, Mg, Zn, Fe, Mn and Cu by atomic absorption spectrophotometry.

Analysis of competition.

Statistical analysis were performed using General Linear Models and Regression procedures (Freund et al., 1986). Per plant dry weight data were analyzed using analysis of variance with a complete factorial treatment arrangement. Main factors were CP rate, total density, composition (mixture or monoculture) and species. Data for monocultures of a density of one plant per pot were excluded from this analysis.

Relative yield of a species grown in a 1:1 mixture is defined as the yield of the species in mixture divided by the yield obtained in monoculture of the same species (DeWit and Van Den Bergh, 1965). Relative yields were calculated for each species, P rate and density combination. These data were analyzed as a complete factorial arrangement with the main factors being P rate, density and species.

A relative crowding coefficient was determined using the techniques of Rejmanek et al. (1989) and was used as an indicator of the relative aggressiveness of one species versus another. It is defined as:

$$RCC_{12} = W_{1t}/W_{2t}/W_{1P}/W_{2P}$$

The two component species of the mixture are identified as 1 and 2. Mean yields per plant for the plants grown in mixture are W_{1t} and W_{2t}. Mean yields per plant for monocultures are given by W_{1P} and W_{2P}.

Techniques of Jolliffe et al. (1984) were used to calculate relative monoculture responses (RMR) and relative mixture responses (RXR) at each of the CP rates for the Gainesville and the spring Belle Glade experiments. Relative monoculture responses were calculated from the equation:

$$RMR = (Y_p - Y_m) / Y_p$$

The yield obtained in monoculture is represented by Y_m. The Y_p is a hypothetical predicted yield which would result if no competition occurred (Jolliffe et al., 1984). It is derived from the initial slope of the relationship between yield and density. In this study Y_p was calculated from the relationship given by Roush et al. (1989):

$$Y_p = (Y_{max} / K_n) (N)$$

Where Y_{max} is the constant final yield, K_n is the density at which one half of Y_{max} is achieved and N is the plant density

for the yield prediction of interest. Determination of Y_{max} is based on the relationship between yield and density:

$$y^{-1} = a + bx^{-1}$$

where y is yield and x is density. The letters a and b are the intercept and slope, respectively. The equation can be rearranged as:

$$y = x / ax + b$$

As density increases to the point where further yield increases become negligible, Y_{max} is predicted by Y.

Mixture data RXR was determined from the equation

$$RXR = (Y_{mr} - Y_x) / Y_{mr}$$

where Y_x is the yield of a species in mixture and Y_{mr} is the monoculture yield determined from the regression of yield on density in the monocultures.

Results and Discussion

Preliminary Studies

Plant dry weight data for preliminary 1 are given in Table 4.3. Each of the main effects species, density and CP rate influenced plant dry weight. Spiny amaranth dry weight was 51% greater than that of lettuce when both species were grown in monoculture. The effect of CP rate on plant dry weights is given in Figure 4.1. Although there was no significant interaction between CP rate and species, data are presented for the individual species to clearly show the

Table 4.3 The effect of species, plant density and calcium phosphate soil amendment rate (P) and their interactions on shoot dry weight in preliminary experiment 1.

Main Effect	Shoot Dry Wt. ($g \cdot pot^{-1}$)
Species (S)	
lettuce	1.84
spiny amaranth	2.78
Significance[a]	***
Density[b] (D)	
4	1.26
8	1.91
16	2.82
32	3.25
Significance	***
P[c]	
0	1.14
0.36	2.32
0.72	2.74
1.44	3.05
Significance	***

Interaction	- - significance - -
SxD	ns
SxP	ns
DxP	ns
SxDxP	ns

[a]Level of significance for the main effect.

[b]Densities are in plants per pot.

[c]Grams calcium phosphate per L soil.

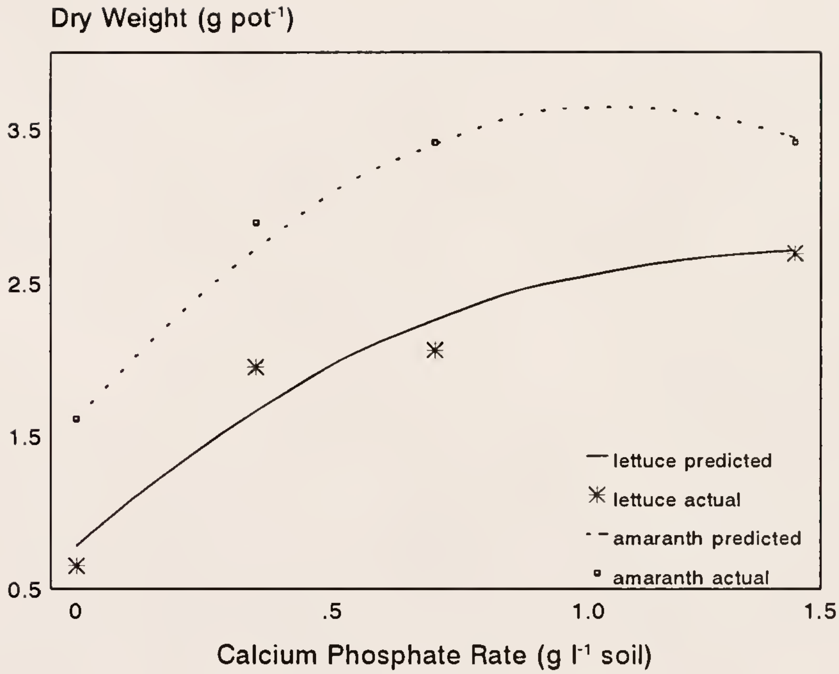

Figure 4.1. The effect of calcium phosphate on plant dry weight in preliminary 1. Phosphorus rate in grams $Ca(H_3PO_4)_2$ per L soil. Predicted line equations are $y=0.78+2.83x-0.926x^2$ ($R^2=0.44$; $p=0.001$) for lettuce and $y=1.6+3.72x-1.543x^2$ ($R^2=0.25$; $p=0.001$) for spiny amaranth.

response of each. For each of the species, dry weight responded in a quadratic fashion with increased CP.

The effect of CP rate on dry weights of spiny amaranth and lettuce in preliminary 2 is given in Table 4.4. The main effect species and an interaction between species and CP rate influenced plant dry weight. The effect of CP rate on plant dry weight of lettuce and spiny amaranth are shown in Figure 4.2. Lettuce dry weight responded positively in a quadratic fashion to increased CP while spiny amaranth dry weight decreased in a linear fashion.

The effect of CP on lettuce dry weight in Preliminary 3 (where spiny amaranth was not evaluated) is given in Figure 4.3. The lettuce dry weight response to CP was of a quadratic nature. In each of Preliminaries 1, 2 and 3, lettuce showed a positive response to CP. In Preliminaries 1 and 2 the greatest lettuce dry weights were obtained with the highest CP rates used. In Preliminary 3, where the highest CP rates exceeded those of Preliminaries 1 and 2, a decline in dry weight was apparent with the highest P rates. In Preliminaries 2 and 3, where a fixed density of 4 plants was used, maximum lettuce dry weights were obtained at the CP rate of 16. Lettuce dry weight at this rate was about 35% greater in Preliminary 3 than in 2. This difference in dry weight suggests that lettuce growth in Preliminary 2 was not ultimately limited by P. The cause of the apparent difference in plant dry weights between these two

Table 4.4 The effect of species and calcium phosphate soil amendment rate (P) and their interaction on shoot dry weight in preliminary 2.

Main Effect	Shoot Dry Wt.[a] (g · pot^{-1})
Species (S)	
lettuce	0.24
spiny amaranth	1.01
Significance[b]	***
P[c]	
0	0.63
0.72	0.65
1.44	0.69
2.26	0.59
2.88	0.58
Significance	***
Interaction	- - level of significance - -
SxP	***

[a]Density of 4 plants per pot

[b]Level of significance for the main effect.

[c]Grams calcium phosphate per L soil.

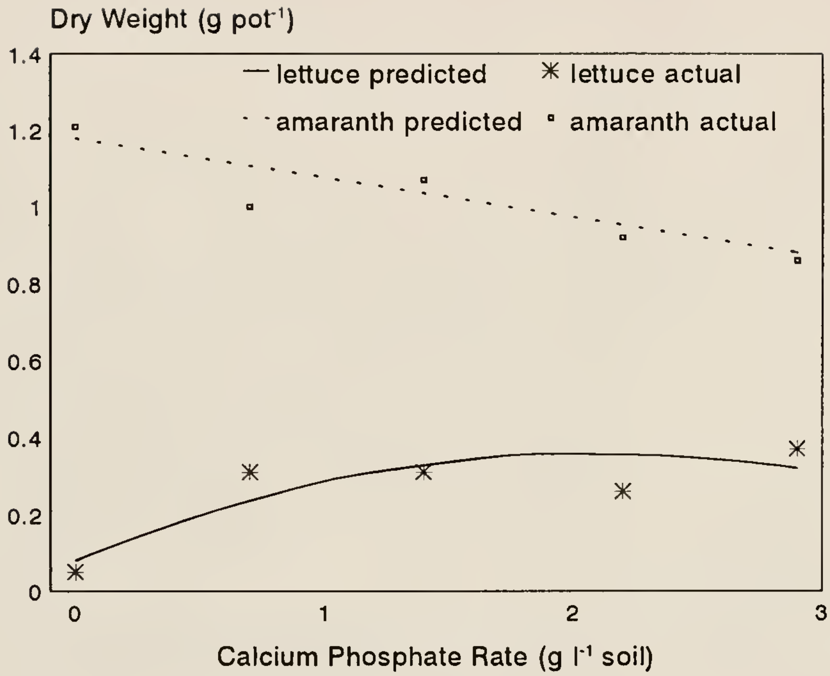

Figure 4.2. The effect of calcium phosphate on plant dry weight in preliminary 2. Phosphorus rates are in grams $Ca(H_3PO_4)_2$ per L soil. Predicted line equations are $y=0.079+0.26x-0.062x^2$ ($R^2=0.53$; $p=0.01$) for lettuce and $y=1.17-0.11x$ ($R^2=0.5$; $p=0.01$) for spiny amaranth.

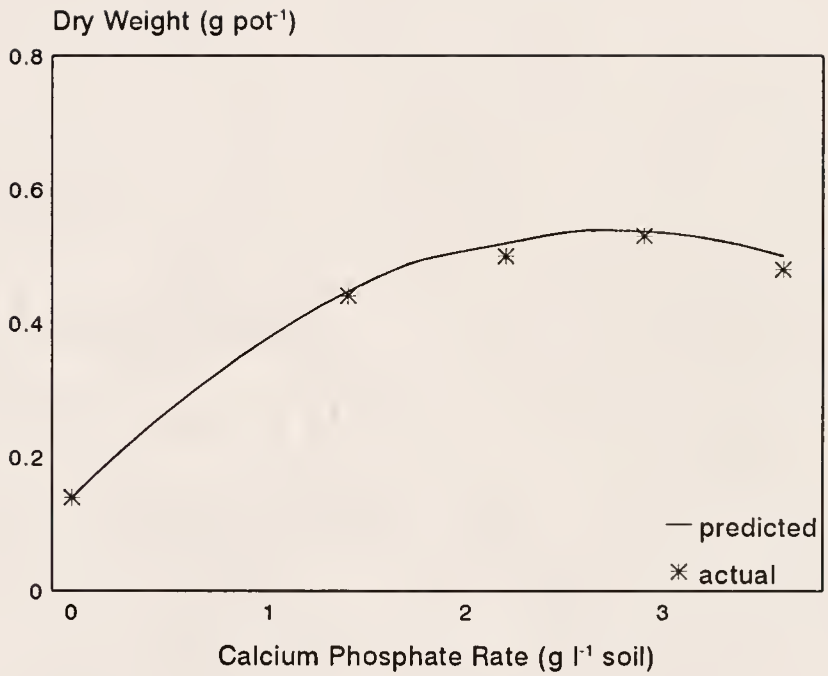

Figure 4.3. The effect of calcium phosphate on plant dry weight in Preliminary 3. Phosphorus rates in grams $Ca(H_3PO_4)_2$ per L soil. Predicted line equation is $y=0.14+0.289x-0.0527x^2$ ($R^2=0.82$; $p=0.001$).

experiments is not known. The response to CP rate obtained in Preliminary 3 is a typical plant growth response to increasing availability of a single nutrient when rates are increased sufficiently to become toxic (Epstein, 1972).

Lettuce was relatively more responsive to soil amendment with CP than was spiny amaranth. Lettuce generally responded to increased CP rate in a positive fashion. An exception was at the highest two rates used in Preliminary 3 where a dry weight reduction became apparent.

The response by spiny amaranth to CP, on the other hand, was erratic. Depending on the experiment, both positive and negative responses were found. The negative responses to CP may have resulted from chemical interactions between P and other elements essential to plant nutrition (Adams, 1980). Such interactions may occur in soil or in the plant. Nutrients for which uptake and metabolism may be interfered with by high P are Fe, Mn and Zn. A condition characterized by necrotic leaf margins on the older leaves often became apparent on spiny amaranth the last several days prior to termination of the experiments. The cause of the condition was not identified but it appeared to be more severe where CP was added to the soil. No nutrient deficiency symptoms were observed on lettuce in these experiments.

Another means by which CP may interfere with plant growth has to do with the cost of nutrient acquisition.

Phosphorus uptake by roots has been found to be negatively correlated with internal P concentrations (Schorring and Jensen, 1984). Net P uptake results from the combined effects of soil to root influx and efflux of P, both of which are active processes. If this is the case with lettuce, the negative growth response to high CP rates may have been a result of the energy cost of the exclusion of excess P required to maintain adequate internal P concentrations. Resource consumption by this process would result in reduced resource availability for other growth processes.

Competition Studies - Monoculture Response to Phosphorus

Gainesville. The CP rates in the Gainesville competition study were selected based on the results of the preliminary experiments. Rate selection was based on the response of lettuce to CP rather than that of spiny amaranth. Three CP rates were selected so that lettuce growth of three levels would be obtained. At the extremes, minimum and maximum growth were intended. A third level was to be intermediate to these; in the range where growth would be responsive to CP. Emphasis was given to the results of Preliminaries 1 and 3 since lettuce growth achieved in Preliminary 2 was relatively less than in these experiments, as previously discussed. A density of 4 plants per pot was chosen to assess the response of lettuce and spiny amaranth

monocultures to CP in the Gainesville competition experiment. The effects of CP and species on plant dry weight are given in Table 4.5. Spiny amaranth dry weight was 3 times greater than that of lettuce. There was a significant response to soil amendment with calcium phosphate. No significant interaction was found between species and CP. In order to clearly assess the response of each species to CP, the affect of CP on lettuce and spiny amaranth are given in Figure 4.4. For lettuce, a significant quadratic response to CP was obtained. For spiny amaranth, linear regression analysis did not account for any variation in dry weight due to CP rate. Means for the treatment not receiving additional CP were compared to those of each CP rate. In all cases, spiny amaranth dry weight was greater when CP was added. Over the three rates where CP was added to the soil, spiny amaranth mean dry weights remained relatively unchanged, indicating that spiny amaranth did not respond to an increasing rate of CP.

Belle Glade - spring. For the Belle Glade competition studies the CP rates were modified in order to obtain smaller responses to the two lower CP rates than were obtained in the Gainesville experiment (Table 4.2). In addition to the rates at which the competition studies were conducted, additional CP rates were included to assess the growth response of spiny amaranth and lettuce monocultures at a density of 4 plants per pot. These treatments were

Table 4.5 The effect of species and calcium phosphate soil amendment rate (P) and their interaction on shoot dry weight of lettuce and spiny amaranth grown in monocultures at a density of 4 plants per pot in the Gainesville competition study.

Main Effect	Shoot Dry Wt. ($g \cdot pot^{-1}$)
Species[a] (S)	
lettuce	0.99
spiny amaranth	3.41
Significance[b]	***
P[c]	
0	0.93
0.27	2.30
1.35	2.62
2.43	2.53
Significance	***
Interaction	- - level of significance - -
SxP	ns

[a]Plants grown at a density of 4 per pot.

[b]Level of significance for the main effect.

[c]Grams calcium phosphate per L soil.

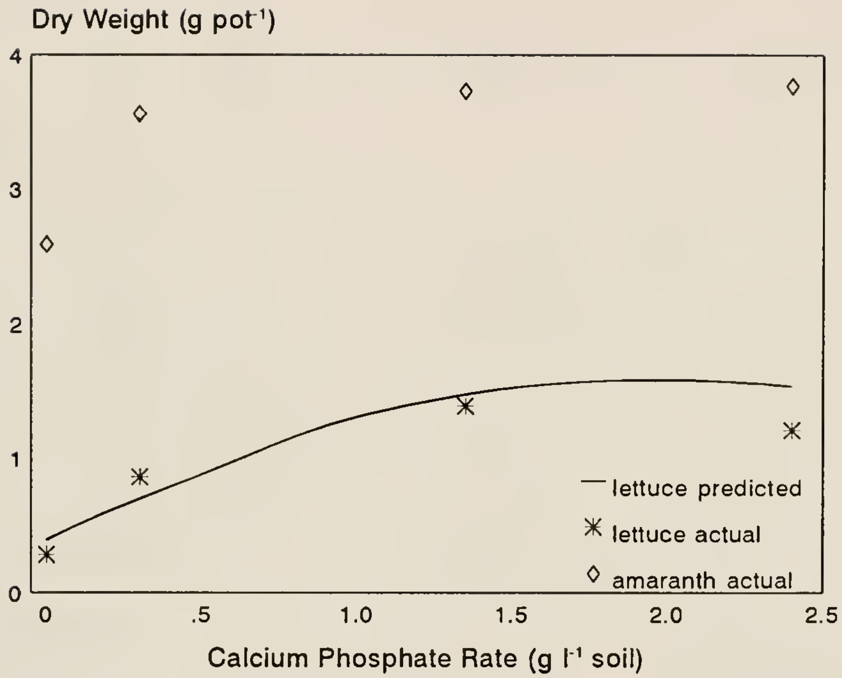

Figure 4.4. The effect of calcium phosphate on the dry weight of lettuce and spiny amaranth grown in monoculture at a density of 4 plants per pot in the Gainesville competition experiment. Calcium phosphate rates are in grams $Ca(H_3PO_4)_2$ per liter soil. Lettuce predicted line equation is $y=0.042+1.59x-0.55x^2$ ($R^2=0.82$; $p=0.001$). Spiny amaranth dry weights were significantly greater at all calcium phosphate rates than where none was applied based on paired means comparisons at alpha=0.05.

established simultaneously with the spring Belle Glade competition study in order to verify the plant growth response to soil amendment with CP at this location. The effect of CP and species on shoot dry weight in this CP rate series is given in Table 4.6. Spiny amaranth dry weights were one tenth greater than those of lettuce. There was a significant interaction between species and calcium phosphate rate. The effect of CP rate on dry weights of lettuce and spiny amaranth are given in Figure 4.5. Lettuce responded in a quadratic fashion to increased CP, as was the case in the Gainesville study. Observed dry weights for lettuce were maximum at the 10.5 rate and remained nearly as high at the 20.5 and 25.5 rates. The actual dry weight at the 15.5 rate is inconsistently low. Spiny amaranth shoot dry weight means are given in Figure 4.5. As in the Gainesville study, no CP rate relationship to spiny amaranth dry weight was found, and, in this case, there were no differences between the no added P treatments and those where no P was added.

There was some inconsistency in how lettuce dry weight responded to CP rate in the spring Belle Glade experiment. In particular, at the CP rate of 15.5 (Figure 4.5) the lettuce dry weight was lower than it was for the 10.5 and 20.5 CP rates. When the Preliminary 1 and 3 and the Belle Glade Competition experiments were established, soil samples were analyzed for P following the amendment of soil with CP.

Table 4.6 The effect of species and calcium phosphate soil amendment rate (P) and their interaction on shoot dry weight of lettuce and spiny amaranth grown in monocultures at a density of 4 plants per pot in the spring Belle Glade competition study.

Main Effect	Shoot Dry Wt. ($g \cdot pot^{-1}$)
Species[a] (S)	
lettuce	2.87
spiny amaranth	3.14
Significance[b]	*
P[c]	
0	1.43
0.09	2.51
0.99	2.92
1.89	3.70
2.79	3.36
3.69	3.59
4.59	3.56
Significance	***
Interaction	- - level of significance - -
SxP	***

[a]Plants grown at a density of 4 per pot.

[b]Level of significance for the main effect.

[c]Grams calcium phosphate per L soil.

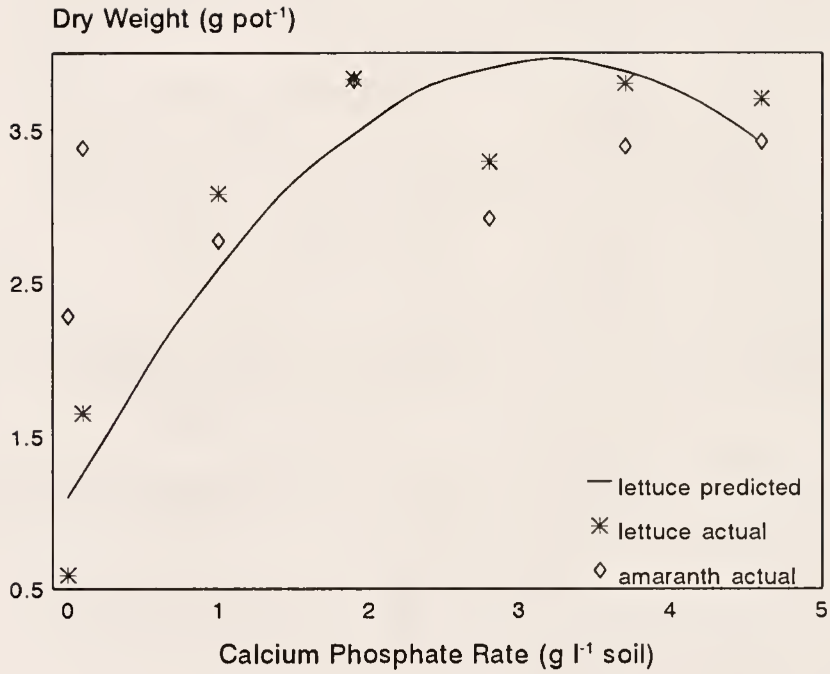

Figure 4.5. The effect of calcium phosphate on plant dry weight in the spring Belle Glade experiment. Calcium phosphate rates are in grams $Ca(H_3PO_4)_2$ per liter soil. Lettuce predicted line equation is $y= 1.1+1.88x-0.31x^2$ (R^2=0.81; p=0.001). Spiny amaranth observed dry weights did not differ between the no added calcium phosphate treatment and any of the rates of calcium phosphate, based on paired means comparisons.

The effect of the amendment of the soil with calcium phosphate (CP) on the soil test index for P (Sanchez, 1990) in Preliminary experiments 1 and 3 and in the spring and fall Belle Glade competition experiments is given in Figure 4.6. Belle Glade 'A' represents the CP rates that were used solely with the monocultures of 4 plants per pot in the spring Belle Glade competition study, as discussed previously. Belle Glade 'B' represents the three CP rates used in the spring Belle Glade competition study. Although no statistical analyses have been performed on this data two trends are evident. For preliminary experiments 1 and 3 and the spring Belle Glade A treatments the soil test P responses to calcium phosphate addition are consistent. For the spring and fall Belle Glade competition experiments, however, the soil test values were somewhat higher. In both of these competition experiments substantially larger volumes of soil were amended with CP than for the other experiments presented in Figure 4.6. Apparently the volume of soil amended had some influence on the response of the soil test index. This may be a result of the technique used to amend soil. Calcium phosphate was initially mixed with a fixed amount of soil, which was subsequently mixed with the remainder of the soil. In the case of the 0.5, 5.5 and 15.5 rates (spring Belle Glade B), for which larger volumes of soil were prepared, relatively larger amounts of CP were mixed with the initial volume of soil than for the P

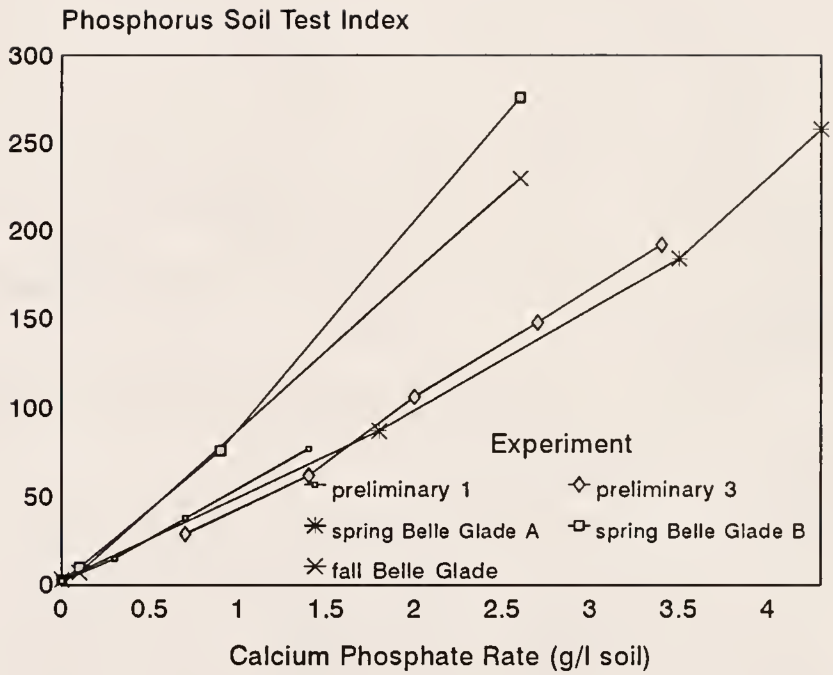

Figure 4.6. The effect of soil amendment with calcium phosphate on the phosphorus soil test index. Calcium phosphate rates are in grams $Ca(H_3PO_4)_2$ per liter soil. Belle Glade A and B correspond to rates used only for the rate response study and rates used for the competition studies, respectively.

rate treatments which were used solely for the assessment of the response of monocultures to CP rates. The high soil analysis P value for the CP rate of 15.5 in the spring Belle Glade competition experiment (Figure 4.6), coupled with the inconsistently low lettuce dry weight obtained at this CP rate (Figure 4.5) suggests that CP may have been excessive for maximum dry weight yields.

Assessment of monoculture response to CP rate indicated similar results for the Gainesville and spring Belle Glade studies. Lettuce responded to CP in these studies in a manner similar to that found in the preliminary experiments. Spiny amaranth, on the other hand, was relatively unresponsive to CP in the Gainesville and spring Belle Glade experiments. It appears that manipulation of phosphorus fertility may be a means of selectively enhancing the growth of lettuce without affecting that of spiny amaranth.

Competition Studies - Plant Dry Weight Analysis

Gainesville. The effects of calcium phosphate, plant density, specie and composition on individual plant weight in the Gainesville study are given in Table 4.7. There were significant interactions between density and species and between composition and species. The reciprocal of individual plant weight versus density is given in Figure 4.7 for each specie. Reciprocals of individual plant weight are typically found to exhibit a linear relationship to

Table 4.7. The effect of calcium phosphate, density, species and composition and their interactions on plant dry weight in the competition experiments.

Treatment[a]	Gainesville	Belle Glade spring	Belle Glade fall
	- - - - dry weight (g · plant^{-1}) - - - -		
Calcium phosphate (P)			
low	0.58	0.48a[b]	0.41a[b]
medium	0.70	0.55b	0.58b
high	0.59	0.61b	0.56b
Signif.[c]	ns	***	***
Density (D)			
2	1.07	1.08	1.03
4	0.71	0.74	0.69
8	0.44	0.46	0.43
16	0.27	0.29	0.28
32	--	0.17	0.16
Signif.	***	***	***
Specie (S)			
lettuce	0.23	0.58	0.31
amaranth	1.01	0.52	0.73
Signif.	***	*	***
Composition (C)			
mixture	0.70	0.56	0.55
monoculture	0.55	0.54	0.49
Signif.	**	ns	ns
Interactions	- - - level of significance - - -		
P x D	ns	*	ns
P x C	ns	ns	ns
P x S	ns	***	ns
D x C	ns	ns	ns
D x S	***	ns	***
S x C	***	*	ns

Table 4.7--continued.

Treatment[a]	Experiment Gainesville	Belle Glade spring	Belle Glade fall
P x D x S	ns	*	ns
P x D x C	ns	ns	ns
P x S x C	ns	*	ns
D x S x C	ns	ns	ns
P x D x S x C	ns	ns	ns

[a]Low, medium and high calcium phosphate levels are equivalent to 0.25, 1.27 and 2.29 g calcium phosphate per L soil, respectively, in the Gainesville study and 0.08, 0.93 and 2.63 g calcium phosphate per L soil, respectively, in the Belle Glade studies. Densities are in plants per pot (12cm diam.). Mixtures are of 1:1 proportion.

[b]Calcium phosphate means within a column followed by a common letter are not different based on paired means comparisons at alpha=0.05.

[c]Level of significance for the treatment.

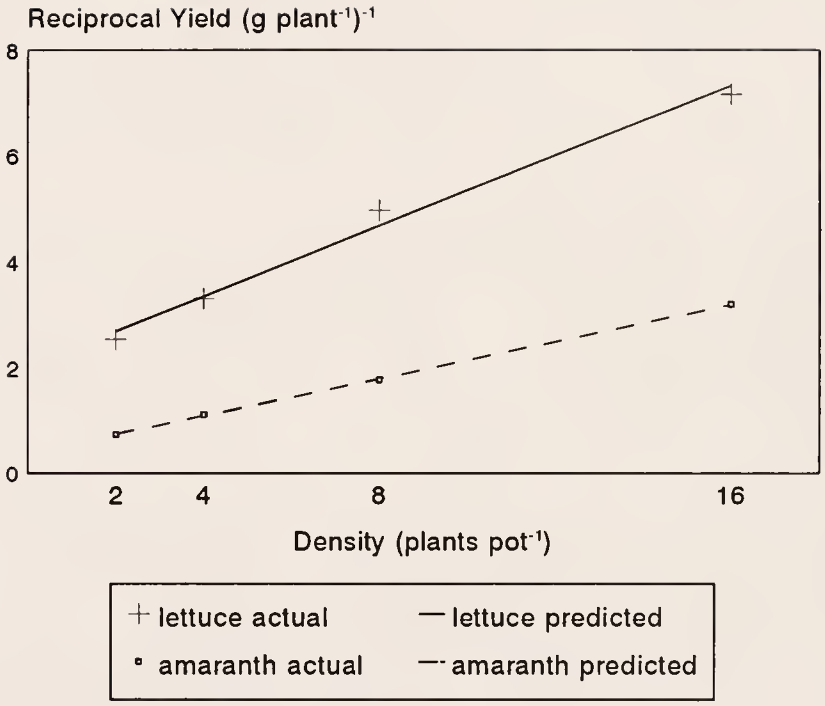

Figure 4.7. The effect of density on the reciprocal of plant dry weight in the Gainesville experiment. Densities are in plants per pot (12 cm diameter). Predicted line equations are y=2.036+0.33x (R^2=0.69; p=0.001) for lettuce and y=0.4-0.175x (R^2=0.89; p=0.001) for spiny amaranth.

density (Radosevich, 1987). This was found to be the case for each of lettuce and spiny amaranth. The species by density interaction suggests that the two species differed in their response to density. The steeper slope of the reciprocal yield plot for lettuce compared to spiny amaranth reflects a more rapid rate of decline in individual plant weight with increased density.

The interaction between species and composition is explored in Table 4.8. Plant weights were greater in mixture than in monoculture for spiny amaranth but did not differ for lettuce. In the case of spiny amaranth, this suggests that the effect of interspecific competition on spiny amaranth in mixture with lettuce was less than the intraspecific competition in monocultures of spiny amaranth.

Belle Glade - spring. The effects of CP, density, specie and composition on individual plant weight in the spring Belle Glade study are given in Table 4.7. The interaction between CP, species and composition is explored in Figure 4.8. At the low CP level there were no differences between mixture and monoculture dry weights for either of the species. At the intermediate CP level, spiny amaranth weight was less in mixture than in monoculture while that of lettuce did not differ. At the high CP level, lettuce weight was greater in mixture than in monoculture while that of spiny amaranth did not differ. This indicates that the initial CP increment resulted in the effects of

Table 4.8. The interaction between plant composition and species for plant dry weight in the Gainesville experiment.

Plant Composition	Species		Within row comparisons[a]
	lettuce	amaranth	
	- - dry wt. ($g \cdot plant^{-1}$) - -		
monoculture	0.27	0.82	*
1:1 mixture	0.20	1.20	*
Within column comparisons[b]	ns	*	

[a]Differences are significant at alpha=0.05 based on paired means comparisons.

[b]Differences are significant at alpha=0.05 based on paired means comparisons.

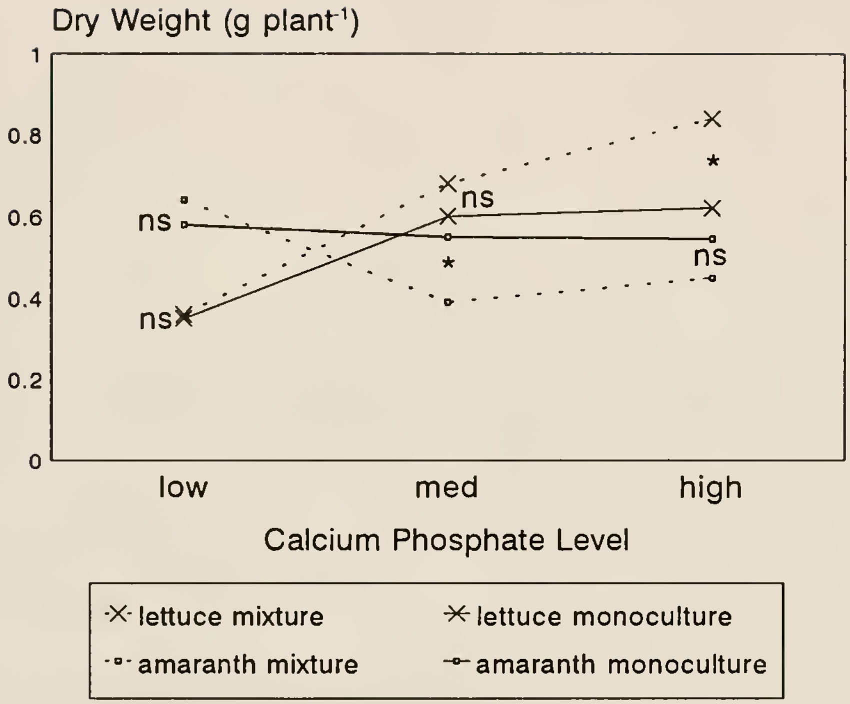

Figure 4.8. The effect of calcium phosphate, composition and species on plant dry weight in the spring Belle Glade experiment. Low medium and high calcium phosphate levels correspond to 0.08, 0.93 and 2.63 g $Ca(H_3PO_4)_2$ per L soil, respectively. Composition (mixture versus monoculture) means within calcium phosphate level and species combinations are significantly different at alpha=0.05 if accompanied by an asterisk.

interspecific competition on spiny amaranth becoming greater than intraspecific effects. For lettuce in monoculture, the intermediate CP level was sufficient to obtain dry weights essentially equivalent to those of the high CP level. When CP is increased to the high level, however, lettuce in mixture yielded greater than in monoculture. This indicates that the final increment of applied P, while not influencing monoculture yields, was beneficial in providing increased interspecific competitive ability to lettuce.

The interaction between CP, density and species on plant dry weight in the spring Belle Glade experiment is explored in Figure 4.9. At the density of 32 plants per pot no differences in plant weights were detected between the CP levels for either species. For spiny amaranth, plant dry weights tended to be greatest at the low CP level but in most instances did not differ between CP levels. A contrasting situation was found for lettuce. At each of densities 2 through 16, dry weights increased between the low and medium CP level. Lettuce dry weights differed between the medium and high CP levels only at the lowest density. This is consistent with the preliminary studies in that lettuce gave a positive response to added CP while spiny amaranth was relatively unresponsive beyond the initial addition of a low rate of CP. The inability to detect differences between CP levels at the density of 32 plants suggests that competition studies conducted at

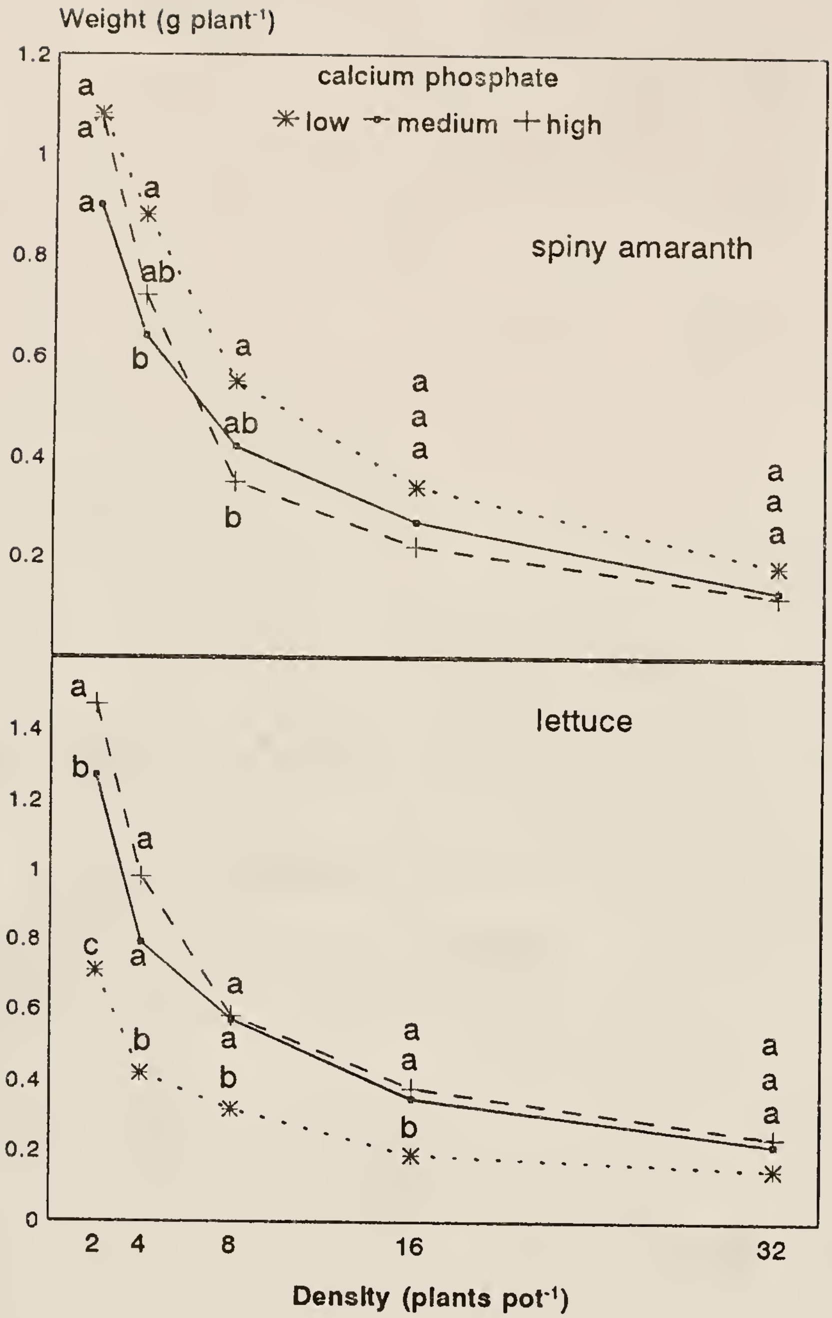

Figure 4.9. The effect of calcium phosphate, species and density on plant dry weight in the spring Belle Glade experiment. Low medium and high calcium phosphate levels are equivalent to 0.08, 0.93 and 2.63 g $Ca(H_3PO_4)_2$ per L soil, respectively. Densities are in plants per pot (12 cm diameter). Calcium phosphate level means within density and species combinations are not significantly different at alpha=0.05 if accompanied by an a common letter.

excessively high densities may not be as useful for assessing P fertility effects than would lower densities.

Belle Glade - fall. The effects of CP, plant density, species and composition on individual plant weight in the fall Belle Glade study are given in Table 4.7. The medium and high CP levels resulted in increased plant dry weights over those of the low level. Unlike the Gainesville and spring Belle Glade experiments, however, there were no interactions between CP and the other experimental factors. There was an interaction between density and species (Table 4.7) which is explored in Figure 4.10. Reciprocals of plant dry weights are plotted here against plant density. For each species, the relationship between the reciprocal of plant dry weight and density was of a linear nature. As was the case in the Gainesville study, the slope of the reciprocal yield plot for lettuce was steeper than that of spiny amaranth, indicating that the lettuce response to density was stronger than that of spiny amaranth. This suggests that intraspecific competition affected lettuce more intensely than spiny amaranth. On the other hand, the fact that no interactions were detected involving the factors species or composition suggests that interspecific and intraspecific competition were comparable. Regardless of this apparent discrepancy, based on plant dry weight analysis, P status did not have a differential affect on the

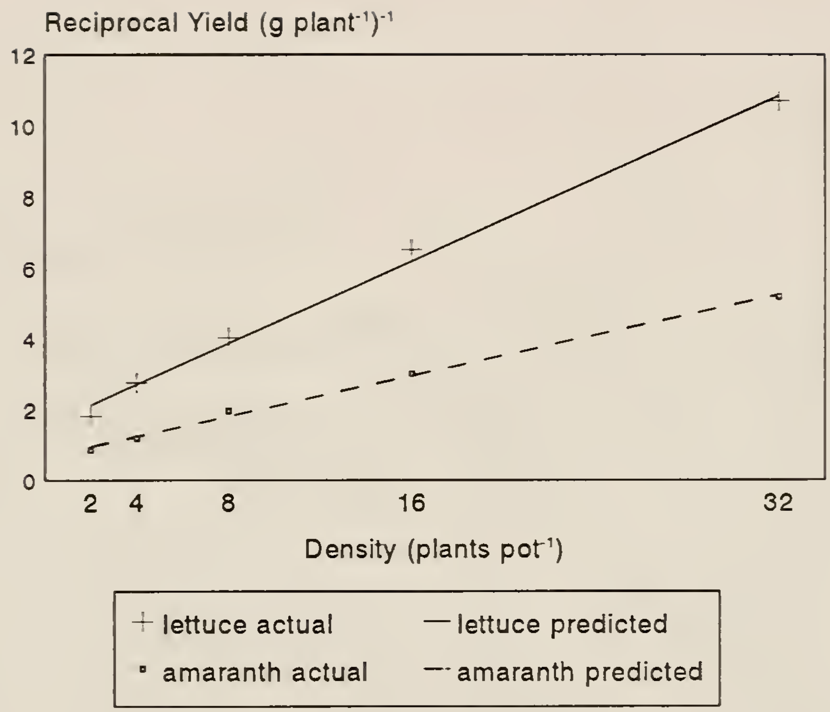

Figure 4.10. The effect of density on the reciprocal of plant dry weight in the fall Belle Glade experiment. Densities are in plants per pot (12 cm diameter). Predicted line equations are y=1.55+0.29x (R^2=0.84; p=0.001) for lettuce and y=0.67-0.14x (R^2=0.83 p=0.001) for spiny amaranth.

other experimental factors, therefore suggesting that it was not influencing competition.

Relative Yield Analysis of Competition

Relative yields (RY) are a measure of the performance of a plant species when grown in mixture relative to its performance in monoculture. Equivalent performance in a 1:1 mixture and monoculture would result in a RY of 0.5. Relative yields in the Gainesville study are given in Table 4.9. The interaction between CP, density and species was significant. The effects of CP and species are explored at the individual densities in Figure 4.11. For spiny amaranth, RY was greater than 0.5 in nearly all cases. This suggests that intraspecific competition occurred for spiny amaranth at all densities and rates of calcium phosphate. Lettuce RY values, on the other hand, were generally less than 0.5. There was a tendency for the RY of lettuce to increase with calcium phosphate level, although this increase was significant only at a density of 4 plants. It is also of interest that increased CP had an effect on the relationship between the RY values of the two species at the intermediate densities of 4 and 8 plants. As the CP level was increased the relative yields of the two species converged. This analysis of RY suggests that P nutrition can improve the ability of lettuce to compete with spiny

Table 4.9. The effect of calcium phosphate, density and species and their interactions on relative yields in the competition experiments.

Effect[a]	Experiment: Gainesville	Belle Glade spring	Belle Glade fall
	- - - - relative yield - - - -		
Calcium phosphate (P)			
low	0.46	0.55	0.56
medium	0.58	0.50	0.56
high	0.59	0.55	0.57
Signif.[c]	ns	ns	ns
Density (D)			
2	0.53	--	0.57
4	0.50	0.51	0.55
8	0.57	0.50	0.55
16	0.58	0.54	0.61
32	--	0.51	0.56
Signif.	ns	ns	ns
Specie (S)			
lettuce	0.37	0.60	0.53
amaranth	0.73	0.46	0.60
Signif.	***	***	*
Interactions	- - - level of significance - - -		
P x D	ns	ns	ns
P x S	ns	***	ns
D x S	ns	ns	ns
P x D x S	*	ns	ns

[a]Low medium and high phosphorus levels are equivalent to 0.25, 1.27 and 2.29 g calcium phosphate per L soil, respectively, in the Gainesville study and 0.08, 0.93 and 2.63 g calcium phosphate per L soil, respectively, in the Belle Glade studies. Densities are in plants per pot (12cm diam.). Mixtures are of 1:1 proportion.

Table 4.9--continued.

[b]Level of significance for the main effect.

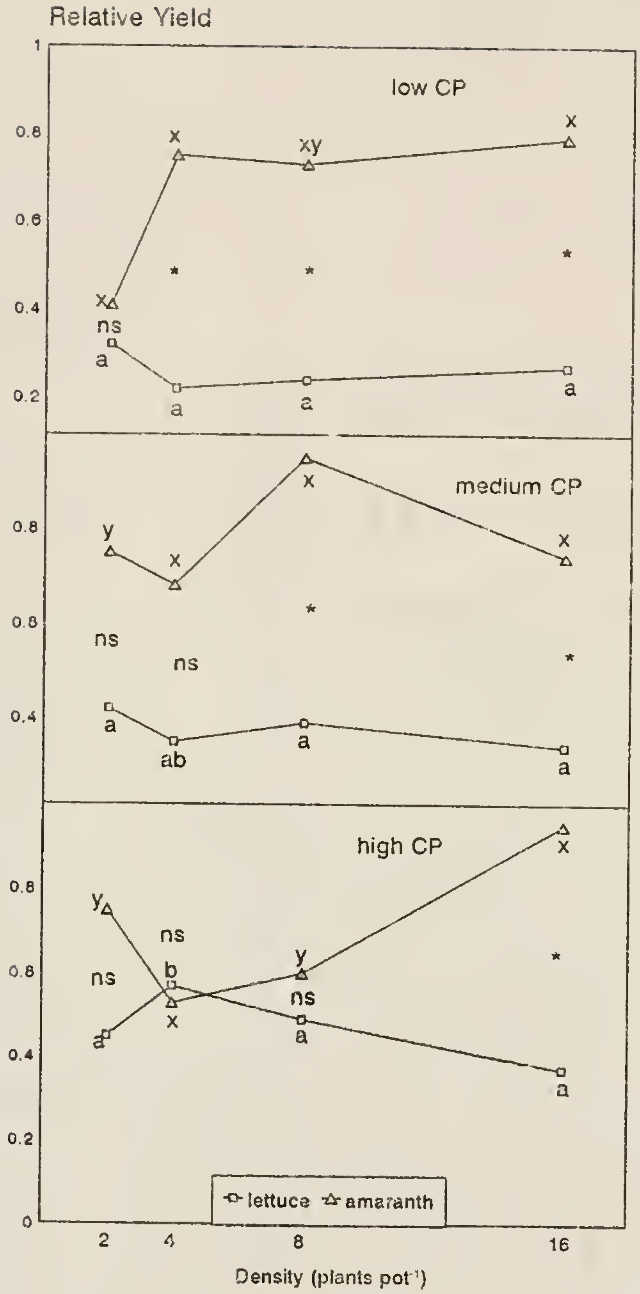

Figure 4.11. The effect of calcium phosphate (CP), density and species (lettuce and spiny amaranth) on relative yield in the Gainesville experiment. Low medium and high calcium phosphate levels are equivalent to 0.25, 1.27 and 2.29 g $Ca(H_3PO_4)_2$ per L soil, respectively. Densities are in plants per pot (12 cm diameter). For each species, calcium phosphate level means within a density are not significantly different at alpha=0.05 if accompanied by an a common letter. Within calcium phosphate level and density combinations, differences between species at alpha=0.05 are indicated by an asterisk.

amaranth even though lettuce is at a competitive disadvantage with the weed.

Relative yields in the spring Belle Glade study are given in Table 4.9. Data for the density of two plants per pot were excluded for this analysis. This was done because RY remained fairly constant among densities 4 through 32, but was greater at the density of two plants (data not presented). This suggested that the low density results were not representative of the general response to density. There was a significant interaction between CP and species, which is explored in Table 4.10. Lettuce and spiny amaranth relative yields did not differ at the lowest CP level. As the CP level was increased, lettuce RY increased while that of spiny amaranth decreased. This indicates that lettuce growth in mixture with spiny amaranth increased with P fertility. At the same time, spiny amaranth growth decreased. An explanation for this would be that the increased lettuce growth resulted in some suppression of the growth of spiny amaranth. Relative yield totals (obtained by summing the relative yields of the two species) remained constant, indicating that these changes were complementary.

The effects of CP, density and species on RY in the fall Belle Glade experiment are given in Table 4.9. In this experiment, RY differed for species but was not influenced by the other experimental factors. Lettuce RY were close to 0.5, suggesting that interspecific and intraspecific effects

Table 4.10 The interaction between species and calcium phosphate level for relative yield in the spring Belle Glade experiment.

Calcium phosphate[a]	Species: lettuce	Species: spiny amaranth	Within row comparisons[b]
	- - relative yield - -		
low	0.52a[c]	0.53a	ns
medium	0.57a	0.41b	*
high	0.68b	0.37b	*

[a]Low, medium and high calcium phosphate levels are 0.08, 0.93 and 2.63 g calcium phosphate per L soil, respectively.

[b]Differences are significant at alpha=0.05 based on paired means comparisons.

[c]Differences within a column are significant at alpha=0.05 based on paired means comparisons.

on lettuce did not differ. The RY of 0.6 for spiny amaranth suggests that intraspecific competition had a greater influence on spiny amaranth growth than did interspecific competition.

Based on the RY analysis, the competitive abilities of lettuce and spiny amaranth were found to differ in their response to P fertility in both the Gainesville and spring Belle Glade experiments. In the spring Belle Glade study, RY indicated that low P favored spiny amaranth while high P favored lettuce. In the Gainesville study, where lettuce growth was substantially less than that of spiny amaranth, RY was dependent not only on species and P fertility but also on density.

In the spring Belle Glade study, and to a lesser degree in the Gainesville study, lettuce relative yields showed a positive response to P fertility. The ability of lettuce to compete interspecifically with spiny amaranth was dependent on P fertility. Spiny amaranth relative yields, however, exhibited a negative response to P fertility. In the monoculture studies, lettuce showed a positive response to P fertility while spiny amaranth was relatively unresponsive. The positive response to P in the RY of lettuce may be explained as being a direct response to the increased growth that resulted from the response to P. The response of the RY of spiny amaranth, on the other hand, was apparently a less direct effect. A plausible explanation is that the P

induced increase in lettuce growth in the mixture resulted in some other factor limiting the growth of spiny amaranth. On possibility is that the larger lettuce leaves reduced the light availability to spiny amaranth.

Relative Crowding Coefficient Analysis of Competition

The relative crowding coefficient (RCC) is an index of competition that quantifies the aggressiveness of one species towards another when grown in mixture. Values are proportional to the competitive ability of the species of interest towards another such that greater values are an indication of increased competitive ability.

The RCC data for the Gainesville study are given in Table 4.11. Interactions between density and species and between CP and species were significant. The density by species interaction is explored in Figure 4.12. Spiny amaranth RCC values increased with density while those of lettuce remained relatively unchanged. This suggests that the competitive effect of spiny amaranth on lettuce, but not of lettuce on spiny amaranth, increased steadily with density. Once certain densities are reached, the RCC should no longer be density dependent (Rejmanek et al., 1989). The increase in RCC with density through the highest level used in the study indicates that densities used may not have been high enough for stabilization of the RCC (Rejmanek et al.,

Table 4.11. The effect of calcium phosphate, density and species and their interactions on relative crowding coefficients (RCC) in the competition experiments.

Treatment[a]	Experiment: Gainesville	Belle Glade spring[b]	Belle Glade fall[c]
	- - - - - - - - - - RCC	- - - - - - - - - -	
Calcium phosphate (P)			
low	37.8	15.0	37.3a[d]
medium	23.3	13.4	19.6b
high	24.3	16.1	21.1b
Signif.[e]	**	***	***
Density (D)			
2	6.5	1.4	2.8
4	16.9	2.4	4.7
8	37.3	6.6	11.8
16	54.2	16.3	31.8
32	--	47.6	78.8
Signif.	***	***	***
Specie (S)			
lettuce	1.7	19.7	7.8
amaranth	55.8	10.1	44.1
Signif.	***	***	***
Interactions	- - - level of significance - - -		
P x D	ns	ns	ns
P x S	**	***	ns
D x S	***	*	**
P x D x S	ns	ns	ns

[a]Low, medium and high phosphorus levels are 0.25, 1.27 and 2.29 g calcium phosphate per L soil, respectively, in the Gainesville study and 0.08, 0.93 and 2.63 g calcium phosphate per L soil, respectively, in the Belle Glade studies. Densities are in plants per pot (12cm diam.). Mixtures are of 1:1 proportion.

Table 4.11--continued.

[b]Analysis of variance performed following log transformation of data values. Non-transformed means are shown in table.

[c]Analysis of variance performed following log transformation of data values+1. Non-transformed means are shown in table.

[d]Means within a column followed by a common letter are not different based on paired means comparisons at alpha=0.05.

[e]Level of significance for the main effect.

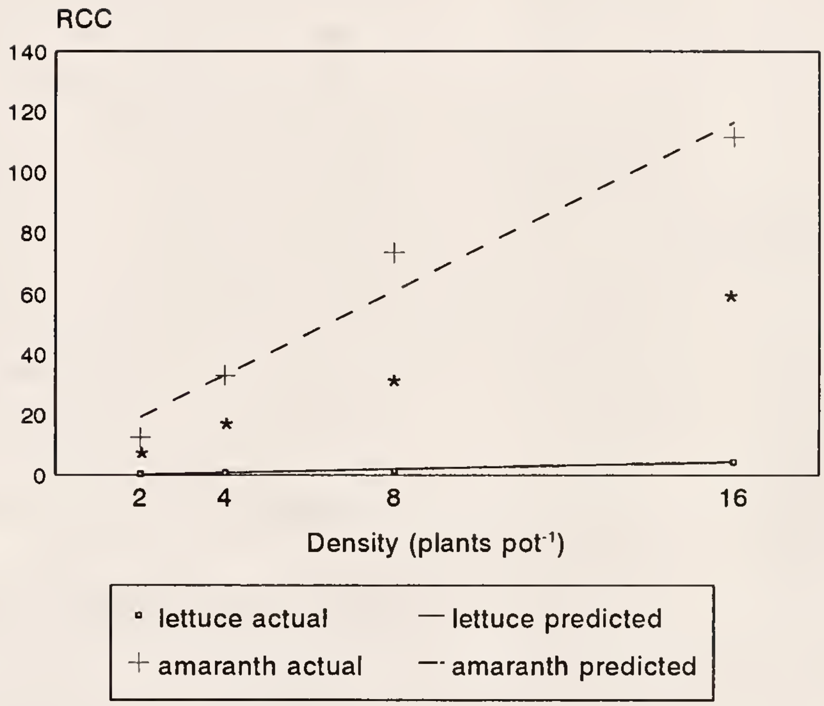

Figure 4.12. The effect of density on the relative crowding coefficient in the Gainesville experiment. Densities are in plants per pot (12 cm diameter). Predicted line equations are $y=-0.387 +0.277x$ ($R^2=0.7$; $p=0.001$) for lettuce and $y=5.54-6.92x$ ($R^2=0.56$; $p=0.001$) for spiny amaranth. Actual values within a density are different at $\alpha=0.05$ if accompanied by an asterisk.

1989). Even so, the differential effect of competition on the two species is still evident.

The interaction between CP and species in the Gainesville experiment is shown in Table 4.12. Spiny amaranth RCC values were greater than those of lettuce at all CP levels. Spiny amaranth RCC values decreased between the low and the intermediate CP levels. This suggests that spiny amaranth was the stronger competitor of the two species in all cases although its competitive ability, relative to that of lettuce, was greatest under the lowest level of P fertility. This suggests that low P conditions favor spiny amaranth over lettuce when the two species are grown in mixture. Relative crowding coefficient analysis of lettuce, on the other hand, indicates that neither density nor calcium phosphate had any effect on its competitiveness with spiny amaranth. This suggests that spiny amaranth growth was essentially unaffected by the presence of lettuce, based on RCC analysis.

Relative crowding coefficients for the spring Belle Glade study are given in Table 4.11. There were significant interactions between density and species and between calcium phosphate and species. The density by species interaction is shown in Figure 4.13. Relative crowding coefficient values for each of lettuce and spiny amaranth increased with density. Lettuce RCC values were greater than those of spiny amaranth at all densities except 4 plants per pot;

Table 4.12 The interaction between species and calcium phosphate level for relative crowding coefficient (RCC) in the Gainesville experiment.

Calcium phosphate[a]	Species: lettuce	Species: amaranth	Within row comparisons[b]
	- - - - RCC	- - - -	
low	1.33a[c]	81.15a	*
medium	1.55a	45.09b	*
high	2.20a	46.49b	*

[a]Low, medium and high calcium phosphate levels are 0.25, 1.27 and 2.29 g calcium phosphate per L soil, respectively.

[b]Means followed by the * are significantly different at alpha=0.05 based on paired means comparisons.

[c]Means within a column followed by a common letter are not significantly different at alpha=0.05 based on paired means comparisons.

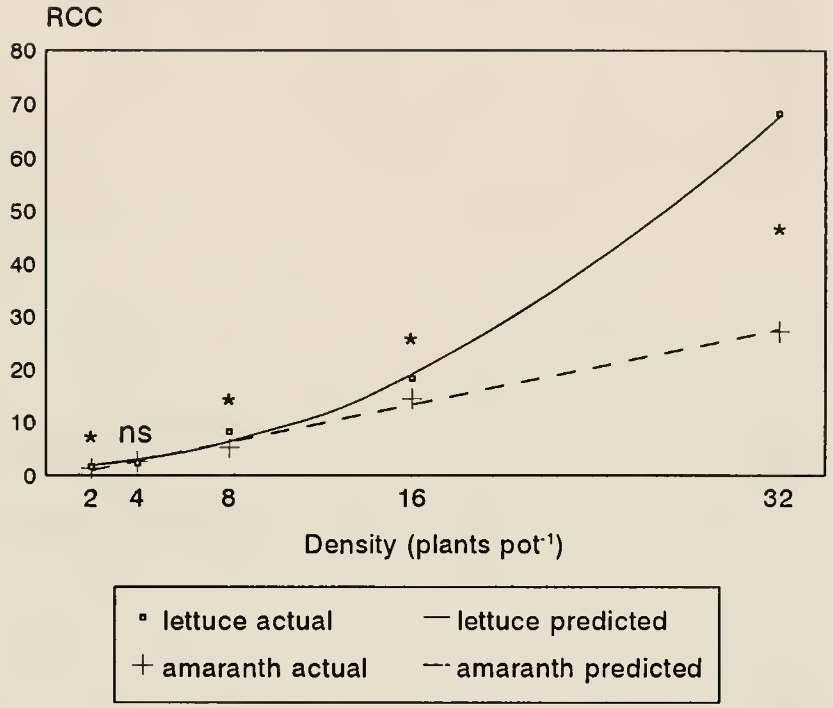

Figure 4.13. The effect of density on the relative crowding coefficient in the spring Belle Glade experiment. Densities are in plants per pot (12 cm diameter). Predicted line equations are $y=1.33+0.15x+0.06x^2$ ($R^2=0.76$; $p=0.001$) for lettuce and $y=-0.877 +0.885$ ($R^2=0.43$; $p=0.001$) for spiny amaranth. Actual values within a density are different at alpha=0.05 if accompanied by an asterisk.

lettuce RCC values being nearly 3 times greater than those of spiny amaranth at the density of 32 plants. This is in contrast to the Gainesville study, in which case spiny amaranth had the higher RCC values. Based on RCC analysis, it appears that with increased density lettuce became a progressively stronger competitor than spiny amaranth. It was also found that the RCC for each species continued to increase through the highest density used. Thus, as in the Gainesville study, densities used were not high enough for stabilization of the RCC.

The interaction between CP and species in the spring Belle Glade experiment is explored in Table 4.13. At the lowest CP level used the spiny amaranth RCC was greater than that of lettuce. As the P source was increased, however, this relationship was reversed. Thus, RCC analysis for this experiment suggests that the competitiveness of each of these species toward one another was differentially influenced by soil P status such that lettuce was favored by increased P availability.

Relative crowding coefficients (RCC) of the fall Belle Glade study are given in Table 4.11. Relative crowding coefficient values were approximately 50 percent greater for the low CP regime than the others but there was no differential response to CP by the two species. There was an interaction between species and density which is explored in Figure 4.14. Spiny amaranth RCC values increased in a

Table 4.13 The interaction between species and calcium phosphate level for the relative crowding coefficient (RCC) in the spring Belle Glade experiment.

Calcium phosphate[a]	Species: lettuce	Species: spiny amaranth	Within row comparisons[b]
	- - - RCC[c] - - -		
low	9.43a[d]	20.64a	*
medium	21.65b	5.24b	*
high	27.89b	4.39b	*

[a]Low, medium and high calcium phosphate levels are 0.08, 0.93 and 2.63 g calcium phosphate per L soil, respectively.

[b]Means followed by the * are significantly different at alpha=0.05 based on paired means comparisons.

[c]Analysis performed on log transformed data. Means are for non-transformed data.

[d]Means within a column followed by a common letter are not significantly different at alpha=0.05 based on paired means comparisons.

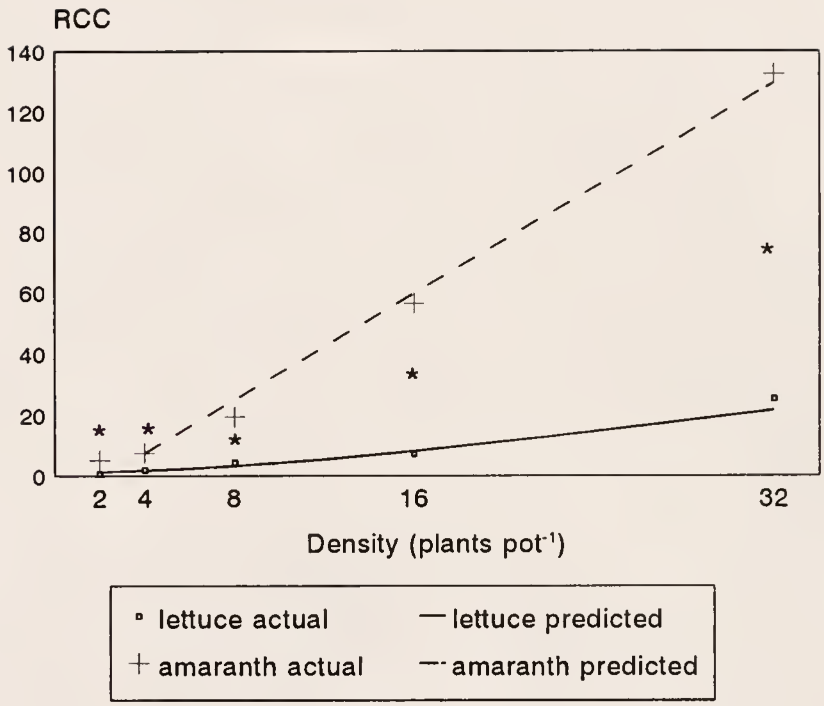

Figure 4.14. The effect of density on the relative crowding coefficient in the fall Belle Glade experiment. Densities are in plants per pot (12 cm diameter). Predicted line equations are $y=0.92+0.13x+0.02x^2$ ($R^2=0.75$; $p=0.001$) for lettuce and $y=-9.96+4.36x$ ($R^2=0.75$; $p=0.001$) for spiny amaranth. Actual values within a density are different at alpha=0.05 if accompanied by an asterisk.

linear fashion with density, which suggests that the competitiveness of spiny amaranth towards lettuce was becoming more intense as density increased. Spiny amaranth RCC values were greater than those of lettuce at all densities. Thus, as in the Gainesville study, spiny amaranth was the more competitive of the two species. In this case, however, there was no differential effect of P fertility on the competitive abilities of either of the species with respect to the other.

In the Gainesville and fall Belle Glade experiments, based on the RCC (Figures 4.12 and 4.14), spiny amaranth was the stronger interspecific competitor of the two species. In the spring Belle Glade experiment, however, the reverse was true. In this case lettuce was more aggressive than spiny amaranth.

The RCC was influenced by density in each of the experiments. For spiny amaranth the response to density was linear in all cases. The nature of the density dependence of the RCC for lettuce, however, differed among the experiments. In the case of the spring Belle Glade experiment, as indicated by the curvilinear response (Figure 4.13), the effect of density on the RCC of lettuce became progrssively greater with increased density. In contrast, in the Gainesville and the fall Belle Glade experiments the lettuce RCC showed a linear response to density. These varied responses to density suggest that RCC analysis of

competition in lettuce is not only dependent on density but also on other factors influential on lettuce growth; factors which were not, however, addressed in this study. The relatively greater lettuce growth in the spring Belle Glade study compared to the others is a probable reason for the variation in the response of the RCC to density.

Relative crowding coefficient analysis indicated that the competitive ability of these species toward one another can be dependent on P fertility. The spring Belle Glade experiment showed that the competitive ability of lettuce with spiny amaranth can be improved by increasing P fertility. This was not so, however, in the Gainesville and fall Belle Glade experiments where the RCC values for spiny amaranth were of a much greater magnitude than those of lettuce. Competitiveness of spiny amaranth towards lettuce, on the other hand, was greatest at the lowest level of CP in both the Gainesville and fall Belle Glade experiments. The fact that these responses were not consistent across experiments suggests that the importance of P on the competitive ability of lettuce is further dependent on factors which have not been addressed in these studies.

Relative Monoculture and Relative Mixture Response Analyses

Relative monoculture response (RMR) is a measure of intraspecific competition which was proposed by Jolliffe et

al. (1984). This analysis has been performed on the results of the Gainesville and spring Belle Glade studies. Values for RMR can range from 0 to 1, such that the higher value indicates increased competition. Relative monoculture response data for the Gainesville study are given in Table 4.14. The interaction between CP and species is explored in Table 4.15. Relative monoculture response values were greater for spiny amaranth than for lettuce at the lower and intermediate CP rates. With increased CP, lettuce RMR increased while spiny amaranth RMR showed no significant change. There was no difference between the two species at the highest level of P. Thus, intraspecific competition of these two species was differentially affected by changes in soil P status. Intraspecific competition in lettuce increased with soil P status while no change was evident for spiny amaranth. This is in concurrence with the dry weight responses of lettuce and spiny amaranthin the monoculture studies. Spiny amaranth was relatively unresponsive to P and its RMR was not influenced P. For lettuce, which was responsive to P, the RMR also showed a positive response to P. Increased lettuce growth due to P resulted in more intense interaction between individual lettuce plants and, consequently, increased RMR values.

Relative monoculture response data for the spring Belle Glade study are given in Table 4.14. The CP by species interaction is explored in Table 4.16. Relative

Table 4.14. The effect of calcium phosphate, density and species and their interactions on the relative monoculture response (RMR) in the Gainesville and spring Belle Glade competition experiments.

Treatment[a]	Experiment: Gainesville	Experiment: Spring Belle Glade
	- - - - RMR - - - -	
Calcium phosphate (P)		
low	0.516	0.514
medium	0.485	0.599
high	0.521	0.677
Signif.[b]	ns	***
Density (D)		
1	0.175	0.188
2	0.334	0.380
4	0.531	0.585
8	0.694	0.727
16	0.803	0.836
32	-	0.903
Signif.	**	***
Specie (S)		
lettuce	0.447	0.625
amaranth	0.568	0.585
Signif.	**	ns
Interactions	- - - level of significance - - -	
P x D	ns	ns
P x S	*	**
D x S	ns	ns
P X D x S	ns	ns

[a]Low medium and high phosphorus levels are equivalent to 0.25, 1.27 and 2.29 g calcium phosphate per L soil, respectively, in the Gainesville study and 0.08, 0.93 and 2.63 g calcium phosphate per L soil, respectively, in the Belle Glade studies. Densities are in plants per pot (12cm diam.). Mixtures are of 1:1 proportion.

Table 4.14--continued.

[b]Level of significance for the main effect.

Table 4.15 The interaction between species and calcium phosphate level for the relative monoculture response (RMR) in the Gainesville experiment.

Calcium phosphate[a]	Species		Within row comparisons[b]
	lettuce	amaranth	
	- - - - RMR - - - -		
low	0.41a[c]	0.63a	*
medium	0.42ab	0.55a	*
high	0.52b	0.53a	ns

[a]Low, medium and high calcium phosphate levels are 0.25, 1.27 and 2.29 g calcium phosphate per L soil, respectively.

[b]Means followed by the * are significantly different at alpha=0.05 based on paired means comparisons.

[c]Means within a column followed by a common letter are not significantly different at alpha=0.05 based on paired means comparisons.

Table 4.16 The interaction between species and calcium phosphate level for the relative monoculture response (RMR) in the spring Belle Glade experiment.

Calcium phosphate[a]	Species lettuce	Species amaranth	Within row comparisons[b]
	- - - - RMR - - - -		
low	0.56a[c]	0.52a	ns
medium	0.66b	0.53a	*
high	0.65b	0.70b	ns

[a]Low, medium and high calcium phosphate levels are 0.08, 0.93 and 2.63 g calcium phosphate per L soil, respectively.

[b]Means followed by the * are significantly different at alpha=0.05 based on paired means comparisons.

[c]Means within a column followed by a common letter are not significantly different at alpha=0.05 based on paired means comparisons.

monoculture response values differed between species only at the intermediate level of P, being greater for lettuce than spiny amaranth. For each species, an increase in CP level resulted in an increase in intraspecific competition as measured by RMR. The RMR increase occurred between the low and medium CP levels for lettuce. For spiny amaranth, RMR was greater for the highest CP rate than the two lower rates.

Plant density had a significant effect on RMR in each of the experiments (Table 4.14). There were no interactions between density and the experimental factors CP and species. This suggests that density was not a critical factor in the assessment of the effect of CP on intraspecific competition for these two plant species. Although the RMR values were density dependent, lack of interaction between density and species suggests that the effect of density was similar for both species. The effects of P fertility were similarly not found to differ with density.

The relative mixture response (RXR) is a measure of the effect of competition on a plant species grown in mixture and accounts for the combined effects of interspecific competition and changes in intraspecific competition that result from the reduction in density of the individual species when grown in mixture. This analysis has been performed on the results of the Gainesville and spring Belle Glade experiments. Data for the Gainesville study are given

in Table 4.17. Of the main effects, only species influenced the RXR. The higher value for lettuce indicates that the effects of competition on lettuce in mixture were greater than those affecting spiny amaranth. This suggests that spiny amaranth was a stronger interspecific competitor than was lettuce in this mixture.

Relative mixture response data for the spring Belle Glade study are given in Table 4.17. The interactions between CP and species is explored in Table 4.18. At the lowest CP level, RXR values of the two species did not differ. At the higher levels of P, RXR values were greater for spiny amaranth than for lettuce, indicating that interspecific competition was having a relatively greater affect on the weed than the crop. The effects of competition on spiny amaranth in mixture increased with the initial CP increment and remained unchanged thereafter. For lettuce, RXR was less at the high CP level than at the lowest level. This suggests that the effects of competition on lettuce in mixture with spiny amaranth were greater at low levels of P availability. The effects of competition on the two species, as measured by RXR in this study, were differentially modified by changes in P fertility; low fertility favoring spiny amaranth while lettuce was favored by higher fertility.

In a two species mixture, individual plants will be influenced by both intraspecific and interspecific

Table 4.17. The effect of calcium phosphate (P) application, plant density and species and their interactions on the relative mixture response (RXR) in the Gainesville and spring Belle Glade competition experiments.

Main Effect[a]	Experiment	
	Gainesville	Belle Glade
	- - - - RXR - - - -	
(P)		
low	0.461	0.448
medium	0.412	0.500
high	0.401	0.470
Signif.[b]	ns	ns
Density (D)		
2	0.404	0.431
4	0.446	0.499
8	0.443	0.496
16	0.405	0.479
32	-	0.455
Signif.	ns	ns
Specie (S)		
lettuce	0.627	0.411
amaranth	0.222	0.535
Signif.	***	***
Interactions	- - - level of significance - - -	
P x D	ns	ns
P x S	ns	***
D x S	ns	ns
P X D x S	ns	ns

[a]Low, medium and high phosphorus levels are equivalent to 0.6, 3.2 and 5.8 g calcium phosphate per pot, respectively, in the Gainesville study and 0.2, 2.2 and 6.2 g calcium phosphate per pot, respectively, in the Belle Glade study. Densities are in plants per pot (12cm diam.).

[b]Level of significance for the main effect.

Table 4.18 The interaction between species and calcium phosphate level for the relative mixture response (RXR) in the spring Belle Glade experiment.

Calcium phosphate[a]	Species: lettuce	Species: amaranth	Within row comparisons[b]
	- - - - RXR	- - - -	
low	0.47a[c]	0.42a	ns
medium	0.41ab	0.59b	*
high	0.35b	0.59b	*

[a]Low, medium and high calcium phosphate levels are 0.08, 0.93 and 2.63 g calcium phosphate per L soil, respectively.

[b]Means followed by the * are significantly different at alpha=0.05 based on paired means comparisons.

[c]Means within a column followed by a common letter are not significantly different at alpha=0.05 based on paired means comparisons.

competition effects (Jolliffe et al., 1984). The intraspecific competition in the monocultures of these studies was measured by the RMR. In the Gainesville experiment, plant dry weight variation due to P fertility was only detected in the monoculture P response analysis (Figure 4.4). The RMR indicated, however, that intraspecific competition in lettuce was greater at the high than the low fertility levels. The RMR in the spring Belle Glade experiment indicated that intraspecific competition for lettuce and spiny amaranth was augmented by increased P fertility (Table 4.16). For lettuce, the positive response of RMR to P fertility in the spring Belle Glade study (Table 4.16) is consistent with the positive response of plant dry weight to P (Figure 4.9). As would be expected, the intensity of competition (Welden and Slauson, 1986), was greatest where growth was potentially greatest. For spiny amaranth, however, the RMR suggests increased intraspecific competition (Table 4.15) between the medium and high CP levels even though no differences in dry weight were found here (Figure 4.9). This may be attributed to calculation of RMR being strongly dependent on yields obtained at low densities (Jolliffe et al., 1984). Spiny amaranth dry weights at the high CP level decreased to a greater extent over the densities of 2 to 8 plants than was the case for the lower CP levels (Figure 4.9). The combined effects of the greater dry weight at the low density and the lower dry

weights at the higher densities may be the cause of the RMR value for spiny amaranth being greater at the high CP levels than at the two lower ones. Consequently, while the lettuce RMR response to P fertility parallelled the dry weight response of lettuce in the Belle Glade experiment this was not the case for spiny amaranth. For spiny amaranth, while dry weight differences were essentially not detected for P fertility levels, RMR indicated that intraspecific competition did increase with P. The RMR analysis therefore suggests that lettuce intraspecific competition increased with P fertility under the two contrasting levels of growth (as reflected in dry weight) that were obtained in the Gainesville and spring Belle Glade studies.

Presentation of plant dry weight yields as the reciprocal of individual plant dry weights (Radosevich, 1987) in the Gainesville and fall Belle Glade experiments indicated that increased plant density had a predictable effect on plant dry weight, which would be attributed to more intense competition. In the spring Belle Glade study, however, these yield to density relationships were found to be differentially influenced by P fertility (Table 4.19). Plant dry weight analysis also suggested differential interspecific versus intraspecific competition for spiny amaranth, but not lettuce, in the Gainesville experiment (Table 4.8). Spiny amaranth was less affected by competition in mixture than in monoculture. This would be

Table 4.19 Equations for the regression of the reciprocal of individual plant weight on density in the spring Belle Glade competition experiment.

Species	Calcium phosphate[a]	Equation
lettuce	low	$y=0.92+0.34x-0.005x^2$ ($r^2=0.95$; $p=0.001$)
"	medium	$y=0.53+0.17x-0.0015x^2$ ($r^2=0.95$; $p=0.001$)
"	high	$y=0.64+0.12x$ ($r^2=0.89$; $p=0.001$)
spiny amaranth	low	$y=0.63+0.15x$ ($r^2=0.95$; $p=0.001$)
"	medium	$y=0.8+0.22x$ ($r^2=0.82$; $p=0.001$)
"	high	$y=0.79+0.24x$ ($r^2=0.86$; $p=0.001$)

[a]Low medium and high calcium phosphate levels correspond to 0.08,0.93 and 2.63 g calcium phosphate per l soil, respectively.

expected due to the relatively reduced lettuce growth in general compared to that of spiny amaranth. For the spring Belle Glade experiment, competitive relationships between the two species were additionally influenced by P fertility. As previously discussed, increases in P fertility resulted in lettuce, but not spiny amaranth, becoming a relatively better competitor.

The relative yield analyses indicated that optimization of P fertility can benefit lettuce growing in the presence of spiny amaranth when lettuce is at a competitive disadvantage with the weed, as occurred in the Gainesville experiment, as well as when the crop and the weed are at more comparable competitive terms, as in the spring Belle Glade experiment. The results of the fall Belle Glade study indicated, however, that other factors can overshadow the effects of P fertility on competition. In this case, P fertility was not found to have any influence on RY.

Relationships between density and RCC were generally found to be linear. However, in the spring Belle Glade study where lettuce was competitive, a curvilinear response was obtained. This suggests that the two species were differentially impacted by alteration of density; the interspecific competitive ability of lettuce being more strongly influenced by density than was the competitive ability of spiny amaranth. Regardless of the influence of density on the RCC, the index was sensitive to the affects

of P fertility on the two species, and responded in a manner similar to the RY.

The experimental factor plant density was used in these studies in order to address the question of plant density influences interspecific competition. Its inclusion enabled the comparison of methods of assessment of competition that has been made here. Although density was used as an experimental method, rather than a factor of primary interest, the results of the study provide some indication of how density influenced the competitive abilities of lettuce and spiny amaranth. When plotted as reciprocals, plant dry weights of lettuce and spiny amaranth responded to density in a typical fashion (Radosevich, 1987) in most instances. An exception was for lettuce in the spring Belle Glade experiment (Table 4.19), in which case the effect of density was more pronounced with the highest P availability level (Figure 4.9). Under conditions of high P, in which growth was most rapid, increased density resulted in more pronounced reductions in plant dry weight than under the lower P regimes. Therefore, deviation from the linear relationship between density and recipprocal yield was indicative of inadequate availability of the below-ground resource P.

Relative crowding coefficients were found to be density dependent. In the Gainesville and fall Belle Glade experiments, where spiny amaranth was more competitive than

lettuce, the impact of spiny amaranth competition on lettuce increased in with density in a constant fashion across the range of densities used. In the spring Belle Glade experiment lettuce was more competitive than spiny amaranth at the higher levels of P fertility. In this case, the impact of lettuce competition on spiny amaranth became progressively greater as density was increased. The impact of spiny amaranth on lettuce, on the other hand, was constant as in the other studies. Variation in density, therefore, differentially effected the way in which these species interacted with one another when competing interspecifically.

No trends of density dependency were found for relative yields, as was the case for dry weights and RCC. One factor which would have contributed to this is that for RY, mixture yields are given as a fraction of monoculture yields which have been normalized to be equal to 1. Assuming equivalent interspecific competition for the two species of the mixture, density would not be expected to influence the RY or the RCC results while it would influence the dry weight analysis.

The source of the deviation between the RCC and the RY regarding density dependency may be that the RCC is a function of the response by both species in the mixture to density. Relative yield effects, on the other hand, are

based solely on the response to density of the species in question.

With the RXR, differential affects of P fertility on the two species were suggested in the spring Belle Glade experiment. Increased P fertility resulted in decreased interspecific competition effects on lettuce while effects on spiny amaranth were increasing. This is in accordance with the findings of the RCC in this experiment. This would be expected since the RXR approach was developed to address plant density related limitations of the replacement series approach to the analysis of competition (Jolliffe et al., 1984). In the present studies, the replacement design was conducted at a series of densities. Since the P response did not interact with density for the RCC in the spring Belle Glade experiment the effect of P is averaged across densities in Table 4.13. Conducting replacement series studies at several densities is one way of determining the density dependence of competitive interactions (Jolliffe et al., 1984).

Unlike the RCC and dry weight analysis, RXR was not found to be influenced by density. The RXR is an indice derived for a given species from measurement of the combined effects that inter- and intraspecific competition have on the species. It is a measure of how the effects of competition on a plant differ between mixture and monoculture. The lack of any effect of density on RXR

suggests that the relationships between inter- and intraspecific for the species in this mixture were not density dependent. In studies on lettuce competition with common groundsel (Senecio vulgaris L.), the RXR was similarly not found to be dependent on density (Paul and Ayres, 1987).

The competitive relations between lettuce and spiny amaranth differed among the three studies reported here. An underlying difference is the dry weights obtained for lettuce and spiny amaranth in the studies. In the Gainesville and fall Belle Glade experiments, plant dry weights were 4 and 2.3 times greater for spiny amaranth than lettuce, respectively. In the spring Belle Glade experiment, however, lettuce dry weights were 11% greater than for spiny amaranth. Possible causes contributing to these differences would include solar radiation and temperature (Gardner et al., 1985) and mineral nutrition (Mengel and Kirkby, 1987). In the case of the Gainesville competition study, lettuce germination occurred 2-3 days later than that of spiny amaranth. This may have been the result of thermodormancy of lettuce, which can result in delayed seed germination (Gray, 1977). This would have resulted in a shorter duration of growth period for lettuce since both species were harvested at the same time. This would have contributed to the plant weight differential between lettuce and spiny amaranth in this study. Such

differences in the relative time of emergence of species grown in mixture can also have a determinant effect on the outcome of competition (Aldrich, 1987; Elberse and deKruyf, 1979).

Temperature has been shown to influence competitive relations between plant species using the C_3 and C_4 carbon fixation pathways (Pearcy et al., 1981). Temperatures above 25C favored the C_4 species while lower temperatures favored the C_3 species. Lettuce is a C_3 species (MacDonald et al., 1987) while amaranthus species are C_4 plants (Patterson, 1985). Daily minimum and maximum air temperatures in the competition studies were lower in the spring Belle Glade experiment than in the others (Table 4.20). Temperature, therefore, may have influenced the outcome of the experiments. Lower temperatures would have favored lettuce, which would be consistent with the increased competitive ability of lettuce in the spring Belle Glade experiment. This also suggests that the ability of lettuce to compete with spiny amaranth during early growth may be dependent on the growing season. In south Florida, temperatures may vary to a similar extent as in these studies. Among the three studies, the greatest responses to P fertility and the smallest differences in growth between the two species were obtained in the spring Belle Glade experiment. For this study the four approaches used to assess the affects of P

Table 4.20 Mean daily minimum and maximum air temperatures for the competition experiments.

Experiment	Temperature (C) Minimum	Temperature (C) Maximum
Gainesville	24.5	35.0
Belle Glade - spring	17.2	28.9
Belle Glade - fall	21.1	31.4

fertility on competition of lettuce and spiny amaranth mixtures (plant dry weight, RY, RCC and RXR) all indicated that increased P conferred a competitive advantage to lettuce and disadvantage to spiny amaranth. For each of plant dry weight, RY and RCC, competition was also dependent on plant stand density. However, the lack of 3-factor interactions by density with species and P fertility suggests that for purposes of assessing the importance of P fertility on competition results are not necessarily dependent on the density used in the study. It is an important consideration, however. For example, plant dry weight response to P fertility was not detected at a density of 32 plants per pot (Figure 4.9) while it was at lower densities. It would be desireable to select densities at which sizeable responses to fertility levels are found.

In the Gainesville study, dry weight response to P fertility was only detected for the monoculture data and lettuce growth was comparatively less than that of spiny amaranth. In this case, P fertility affects on competition were apparent with the RY and RCC but not the RXR. Using the RCC, P fertility affects were only detected in spiny amaranth and indicated that the species competed better at low CP than at the higher levels. Based on the RY analysis, improved competitive ability of lettuce relative to that of spiny amaranth by increased P fertility was suggested. The

improvement was density dependent, however, occurring at the intermediate densities.

These studies provide some evidence of a change in the mechanism of competition as P fertility is modified. One characteristic which would contribute to the competitive ability of a plant under low nutrient availability would be the ability to grow at depleted resource levels (Goldberg, 1990). It follows that competition such as this would be most intense at low levels of nutrient availability. In this sense, spiny amaranth would be considered a better interspecific competitor than lettuce at low P. Relative crowding coefficient analysis in the Gainesville and spring Belle Glade studies suggest that this was the case.

As P fertility was increased it appears that other factors became important in the mediation of competition. This was evident in the plant dry weight analysis of the spring Belle Glade study. In the case of lettuce, the greater dry weights in mixture compared to monoculture at the high CP levels indicated that intense intraspecific competition was occurring. Greater plant weights for lettuce in mixture at high P suggest that lettuce was reseased from intraspecific competition due to the reduction in the density of lettuce plants. Therefore some other factor had become a greater limitation to lettuce growth than P. A probable factor would be light interception, as

lettuce foliage became quite compacted under the high P conditions.

For spiny amaranth, increased P resulted in decreased lettuce growth in mixture compared to monoculture. Increased light interception by lettuce at the expense of spiny amaranth would be a possible cause of this effect. This appears, therefore, to be a situation in which a transition has occurred from P being the limiting factor of competition to one in which another factor becomes predominate. The transition may be from below-ground competition for P to above ground competition for light.

Plant Nutrient Concentrations in the Competition Experiments.

Nutrient concentrations were determined for lettuce and spiny amaranth in the Gainesville and spring Belle Glade competition experiments. Micronutrient data for these studies are given in Appendix B and were within ranges considered adequate for lettuce (Sanchez et al., 1991).

Macronutrient concentrations in the Gainesville experiment are given in Table 4.21. For N, P and K there were no interactions between the main effects. Nitrogen concentrations averaged 2.3% of dry weight for lettuce. A concentration of 2.7% has been reported to be the critical level for lettuce (Beverly, 1984). Nitrogen, therefore, may have been limiting to lettuce growth in the experiment.

Table 4.21. The effect of calcium phosphate (P), species (S), stand composition (C) and stand density (D) and their interactions on macronutrient concentrations in the Gainesville competition experiment.

Main Effect[a]	Nutrient N	P	K	Ca	Mg
P	- - - concentration (% of dry wt.) - - -				
low	2.55	0.41a[b]	7.14a	4.30a	1.06a
medium	2.39	0.60b	7.75b	4.33a	0.99b
high	2.37	0.69c	7.96c	3.83b	0.97b
Signif.[c]	ns	***	**	**	**
S					
lettuce	2.33	0.50	8.18	3.11	0.65
amaranth	2.53	0.64	7.12	5.11	1.34
Signif.	**	***	***	***	***
C					
mixture	2.44	0.58	7.63	4.21	1.00
monoculture	2.42	0.56	7.63	4.09	1.01
Signif.	ns	ns	ns	ns	ns
D					
2	2.62	0.63	7.75	4.18	1.03
4	2.52	0.61	7.94	4.06	0.99
8	2.34	0.54	7.61	4.11	1.00
16	2.26	0.52	7.25	4.23	1.00
Signif.	**	**	*	ns	ns
Interactions	- - - level of significance - - -				
P x D	ns	ns	ns	ns	ns
P x C	ns	ns	ns	ns	ns
P x S	ns	ns	ns	**	***
D x C	ns	ns	ns	ns	ns
D x S	ns	ns	ns	*	ns
S x C	ns	ns	ns	ns	ns
P x D x S	ns	ns	ns	ns	ns
P x D x C	ns	ns	ns	ns	ns
P x S x C	ns	ns	ns	ns	ns

Table 4.21--continued.

Main Effect[a]	Nutrient N	P	K	Ca	Mg
Interactions	- - - level of significance - - -				
D x S x C	ns	ns	ns	ns	ns
P x D x S x C	ns	ns	ns	ns	*

[a]Low, medium and high phosphorus levels are equivalent to 0.25, 1.27 and 2.29 g calcium phosphate per L soil, respectively. Species are lettuce and spiny amaranth. Mixtures are of 1:1 proportion. Densities are in plants per pot (12cm diam.).

[b]Phosphorus application means within a column followed by a common letter are not significantly different at alpha=0.05 based on paired means comparisons.

[c]Significance of the main effect.

Phosphorus concentrations in the Gainesville experiment are given in Table 4.21. Calcium phosphate level had a significant effect on P concentrations such that increased P application resulted in increased tissue P concentration. Tissue P concentration in lettuce averaged 0.5%, which is within the adequacy range of 0.35-0.6% for lettuce (Sanchez et al., 1991) and above the critical level of 0.28% proposed by Beverly (1984).

Potassium concentrations in the Gainesville experiment (Table 4.21) increased with CP addition. The mean concentration of 8.18% K in lettuce is above the 4.8-8% sufficiency range for lettuce (Sanchez et al., 1991).

For each of N, P and K, plant tissue concentrations were affected by species and density. The species affect may be a reflection of the basic genetically fixed uptake potential of each species (Mengel and Kirkby, 1987). The effect of density on nutrient concentration is less easily explained. Although no further analysis has been performed, the general trend with each nutrient was for decreased nutrient concentration with increased density. Two possible explanations are as follows. One is that nutrients were being depleted more rapidly due to the greater number of plants drawing on the nutrient supply. An alternative is that the uptake capacity of the plants was reduced by the plant growth conditions associated with the higher densities. Nutrient uptake by plants is an energy requiring

process (Clarkson, 1985). Apparent reduction in dry weight of individual plants due to increased density (Table 4.7) indicates that there was a reduction in resource availability to individual plants for growth. Such a reduction may have also influenced the availability of energy resources for nutrient uptake. The lack of interaction between CP and the other experimental factors for N, P and K concentration is consistent with the lack of interaction between applied P and the other factors for plant dry weight (Table 4.7).

Calcium and Mg concentrations in the Gainesville experiment are given in Table 4.21. Concentrations of these nutrients in lettuce were within ranges considered sufficient for lettuce (Sanchez et al., 1991) and therefore probably not limiting to lettuce growth in the experiment.

Macronutrient concentrations of the spring Belle Glade experiment are given in Table 4.22. Nitrogen concentrations in lettuce were close to the critical value of 2.7% proposed by Beverly (1984) but less than the sufficiency range of 4-5% suggested by Sanchez et al. (1991). Nitrogen concentrations were affected by CP addition, being greatest at the intermediate level. As in the Gainesville experiment, N concentrations were greater in spiny amaranth than in lettuce. This may be due to genetic differences

Table 4.22. The effect of calcium phosphate (P), species (S), stand composition (C) and stand density (D) and their interactions on macronutrient concentrations in the spring Belle Glade competition experiment.

Main Effect[a]	Nutrient N	P	K	Ca	Mg
P	- - - concentration (% of dry wt.) - - -				
low	3.75a[b]	0.67a	7.61a	2.56a	0.66a
medium	4.43b	1.06b	7.77a	2.62a	0.76b
high	3.40c	1.00c	7.14b	2.12b	0.73b
Signif.[c]	***	***	***	***	***
S					
lettuce	2.97	0.67	7.93	1.51	0.44
amaranth	4.75	1.14	7.08	3.36	0.99
Signif.	***	***	***	***	***
C					
mixture	3.89	0.90	7.29	2.47	0.73
monoculture	3.82	0.91	7.73	2.40	0.70
Signif.	***	***	***	***	***
D					
2	4.20	0.92	7.25	2.42	0.73
4	4.01	0.92	7.55	2.43	0.71
8	3.86	0.91	7.66	2.32	0.72
16	3.71	0.92	7.63	2.46	0.71
32	3.52	0.87	7.44	2.55	0.72
Signif.	***	ns	*	ns	ns
Interactions	- - - level of significance - - -				
P x D	ns	ns	ns	ns	ns
P x C	ns	***	ns	ns	ns
P x S	***	***	***	***	***
D x C	ns	ns	ns	ns	ns
D x S	ns	ns	ns	***	ns
S x C	**	ns	ns	ns	ns
P x D x S	ns	ns	**	ns	ns
P x D x C	ns	ns	ns	ns	ns

Table 4.22--continued.

Main Effect[a]	Nutrient N	P	K	Ca	Mg
Interactions		- - - level of significance - - -			
P x S x C	**	**	ns	ns	ns
D x S x C	ns	ns	ns	ns	ns
P x D x S x C	ns	ns	ns	ns	ns

[a]Low, medium and high phosphorus levels are equivalent to 0.08, 0.93 and 2.63 g calcium phosphate per pot, respectively. Species are lettuce and spiny amaranth. Mixtures are of 1:1 proportion. Densities are in plants per pot (12cm diam.).

[b]Significance of the main effect.

[c]Phosphorus application means within a column followed by a common letter are not significantly different at alpha=0.05 based on paired means comparisons.

between the species. Alternatively, it may be a result of competition between lettuce and spiny amaranth for the nutrient. Nitrogen concentrations also tended to decrease with increased plant density. There was an interaction between CP, species and composition, which is explored in Table 4.23. At the low CP level, N concentrations in spiny amaranth were greater when the plant was grown in mixture than in monoculture. Since lettuce growth as reflected in dry weight was also less at this rate of CP than at the others, it may be that the decreased N concentration in spiny amaranth for the monoculture was a result of intraspecific competition for N in spiny amaranth. Since lettuce growth was suppressed at this CP level, more N would have remained available for spiny amaranth when grown in mixture at low P. Individual plant dry weight for spiny amaranth also tended to be greatest at the low rate of CP (Table 4.6), supporting the idea of a higher degree of intraspecific competition at this CP level. Lettuce N concentration increased with the initial CP increment but not the second one. For spiny amaranth, the second increment of CP resulted in a decline in N concentration. Spiny amaranth plant dry weights, however, were not found to differ between the two highest CP rates (Table 4.7). This suggests that the high CP level may have been interfering with N uptake by spiny amaranth. It also indicates that luxury consumption of N was occurring for spiny amaranth at

Table 4.23 The interaction between species and calcium phosphate and composition for N concentrations in the spring Belle Glade experiment.

Calcium phosphate[a]	composition	Species: lettuce	Species: spiny amaranth	Within row comparisons[b]
		- N conc. - (% of dry weight)		
low	mixture	2.29a[c]	5.40a	*
"	monoculture	2.56a	4.76b	*
medium	mixture	3.34b	5.58a	*
"	monoculture	3.36b	5.43a	*
high	mixture	3.15b	3.62c	*
"	monoculture	3.13b	3.70c	*

[a]Low, medium and high calcium phosphate levels are 0.08, 0.93 and 2.63 g calcium phosphate per L soil, respectively.

[b]Differences are significant at alpha=0.05 based on paired means comparisons.

[c]Differences within a column are significant at alpha=0.05 based on paired means comparisons.

the low level of CP since equivalent yields were obtained while N concentrations differed.

Phosphorus concentrations in the spring Belle Glade experiment are presented in Table 4.22. Phosphorus concentrations differed for the three CP levels and were greatest for the intermediate level. Phosphorus concentrations were also influenced by the interaction between CP, species and composition. This interaction is explored in Table 4.24. Phosphorus concentration in spiny amaranth was influenced by composition. The effect, however, was dependent on the CP rate. Since spiny amaranth plant dry weights were greatest with the low rate of CP (Figure 4.9), it does not appear that growth of the plant was limited by inadequate P nutrition. The importance of the interaction between the mixture and monoculture condition is therefore unclear. For lettuce, tissue P concentration responded to CP and composition in a different manner. Phosphorus concentrations in lettuce increased with each of the increments of applied CP. The initial increment resulted in a three-fold increase in tissue P concentration while the final increment resulted in a relatively smaller increase of 13%. Tissue P concentrations in lettuce did not differ between the mixture and monoculture at any of the CP rates. Thus, P nutrition of lettuce, as reflected in tissue P concentration, was not influenced by the presence of spiny amaranth. In addition, this further supports the earlier

Table 4.24 The interaction between species and calcium phosphate and composition for P concentrations in the spring Belle Glade experiment.

Calcium phosphate[a]	composition	Species: lettuce	Species: spiny amaranth	Within row comparisons[b]
		- - - P conc. - - - (% of dry weight)		
low	mixture	0.26a[c]	1.16a	*
"	monoculture	0.26a	1.00b	*
medium	mixture	0.82b	1.28c	*
"	monoculture	0.84b	1.28c	*
high	mixture	0.91c	0.97b	ns
"	monoculture	0.97c	1.14a	*

[a]Low, medium and high calcium phosphate levels are 0.08, 0.93 and 2.63 g calcium phosphate per L soil, respectively.

[b]Differences are significant at alpha=0.05 based on paired means comparisons.

[c]Differences within a column are significant at alpha=0.05 based on paired means comparisons.

discussion that intraspecific competition in lettuce grown at high P concentrations was due to limitation of a factor other than P.

Potassium, Ca and Mg concentrations in the Belle Glade experiment are given in Table 4.22. Each of these nutrients were within ranges considered adequate for lettuce (Sanchez et al., 1991; Beverly, 1984). Interactions for these nutrients did not appear to be important in providing an explanation for the competitive interactions between lettuce and spiny amaranth.

As a means of assessing the involvement of mineral nutrients in interspecific competition, Hall (1974b) proposed the application of replacement study analysis techniques to nutrient contents in the plant. The nutrient content (i.e. the total amount of a nutrient in the plant) is thus considered a form of yield. One approach to such analysis is to contrast relative yields of nutrients with those of biomass. Interspecific competition for a nutrient is suggested when the RY of the nutrient falls below that of biomass. This analysis was conducted for the Gainesville and spring Belle Glade studies (factorial analysis of variance factors were species, calcium phosphate and density). For the Gainesville study no significant differences were found for relative yields of the nutrients (data not presented). Analysis of variance summaries for nutrient relative yields in the spring Belle Glade

experiment are given in Appendix B. For the nutrients N, P, K, Ca, Mn and Zn interactions were found between species and calcium phosphate. Relative yields of Ca and Zn parallelled those of dry weight, indicating that nutrient contents were not influenced by competition (data not presented).

Nitrogen relative yields are given in Figure 4.15. Dry weight relative yields are given as a reference with which nutrient relative yields can be compared. Nitrogen relative yields deviated from those of dry weight at the low CP level. Dry weight relative yields of each species were 0.5 at this CP level, indicating that the two species were equally competitive. The deviation between relative yields for N and dry weight for lettuce suggest that lettuce N acquisition was reduced under interspecific competition although not to the detriment of yield. For spiny amaranth, N acquisition was increased when grown in mixture with lettuce even though dry weight yield remained unchanged.

Phosphorus relative yields are given in Figure 4.16. For lettuce, the relative yield of P was not affected by CP level. Spiny amaranth relative yield of P was greater at the low CP level than the others. This indicates that, at this CP level, spiny amaranth P acquisition was greater when grown in mixture than in monoculture. This did not confer a competitive advantage to spiny amaranth, however, since dry weight relative yields indicated that competition was equivalent for the two species. This is in accordance with

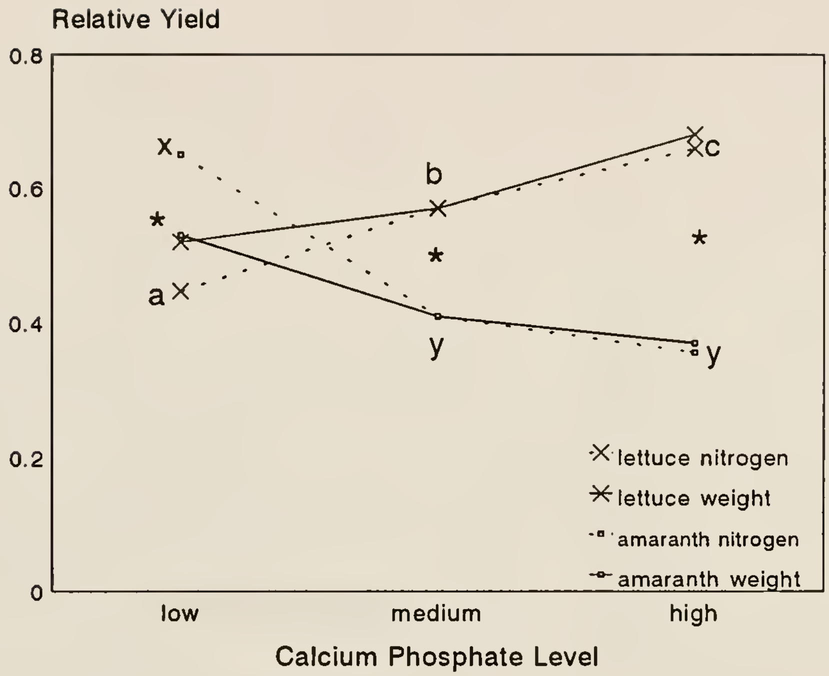

Figure 4.15. The effect of calcium phosphate (CP) on relative yields of nitrogen in lettuce and spiny amaranth in the spring Belle Glade experiment. Low, medium and high CP levels correspond to 0.08, 0.93 and 2.63 g CP per L soil, respectively. Dry weight relative yields are included as a reference. Nitrogen relative yield differences between species, within CP level, are indicated by an asterisk. Calcium phosphate levels within a species are not different if accompanied by a common letter.

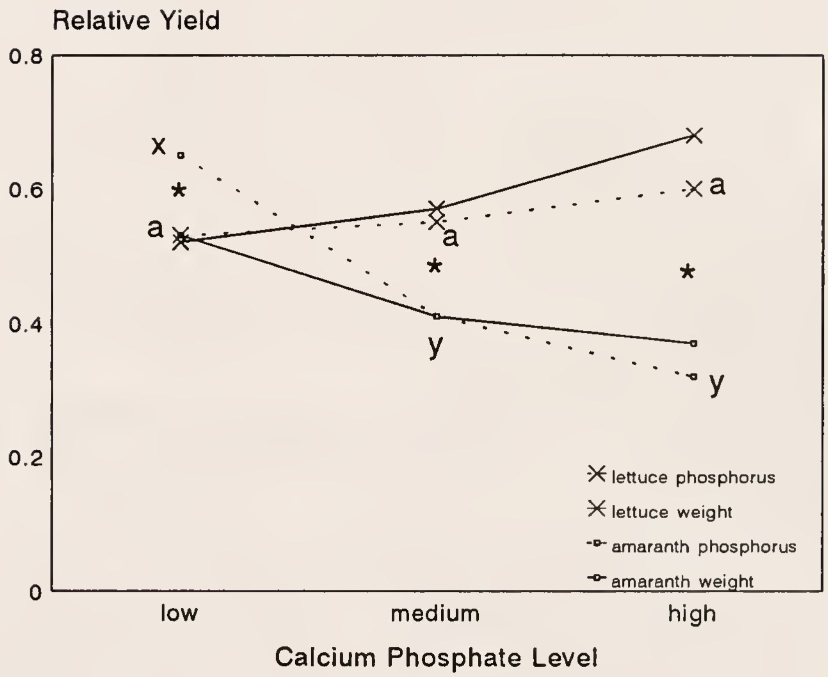

Figure 4.16. The effect of calcium phosphate (CP) on relative yields of phosphorus in lettuce and spiny amaranth in the spring Belle Glade experiment. Low, medium and high CP levels correspond to 0.08, 0.93 and 2.63 g CP per L soil, respectively. Dry weight relative yields are included as a reference. Phosphorus relative yield differences between species, within CP levels, are indicated by an asterisk. Calcium phosphate levels within a species are not different if accompanied by a common letter.the response by spiny

amaranth P concentrations to competition in Table 4.24. This occurred even though spiny amaranth dry weights did not differ between mixture and monoculture at low P (Figure 4.8).

Potassium relative yields are shown in Figure 4.17. Relative yield of K differed for the two species at the medium and high CP levels. Relative yields of K for each species increased with CP level, the increase occurring between the low and medium levels for spiny amaranth and the medium and high levels for lettuce. Based on the interpretation of Hall (1974b), the tendency for the relative yield of K to be less than that of dry weight indicates that acquisition of K by spiny amaranth was a factor limiting the growth of the plant in mixture. Deviations between relative yields of dry weight and K for lettuce were similar to those of spiny amaranth. The importance is less clear in this case, however, since dry weight relative yields are greater than 0.5.

Relative yields of Mn are given in Figure 4.18. Manganese relative yields for lettuce were close to 0.5 at all CP levels. At the medium and high CP levels Mn relative yields were greater for lettuce than spiny amaranth. For both species, nutrient relative yields deviated from dry weight relative yields at the medium and high CP levels. Since the dry weight relative yields of spiny amaranth were below 0.5 at the higher CP levels the Mn relative yields

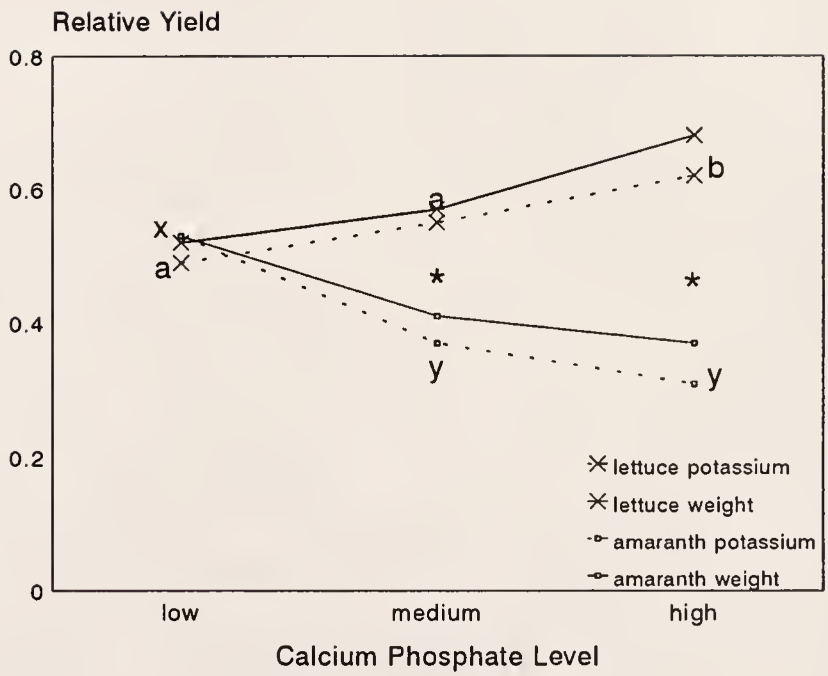

Figure 4.17. The effect of calcium phosphate (CP) on relative yields of potassium in lettuce and spiny amaranth in the spring Belle Glade experiment. Low, medium and high CP levels correspond to 0.08, 0.93 and 2.63 g CP per L soil, respectively. Dry weight relative yields are included as a reference. Potassium relative yield differences between species, within CP levels, are indicated by an asterisk. Calcium phosphate levels within a species are not different if accompanied by a common letter.

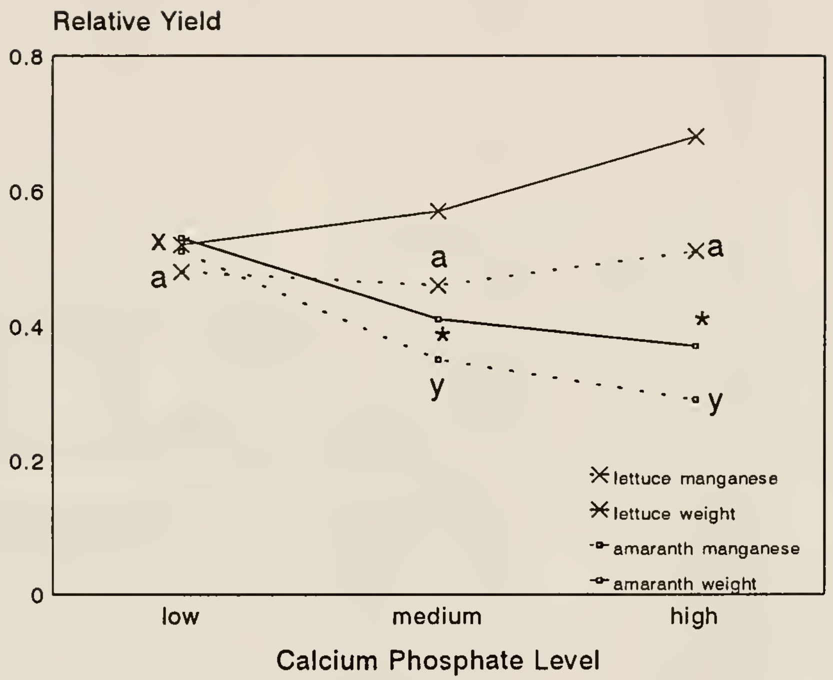

Figure 4.18. The effect of calcium phosphate (CP) on relative yields of manganese in lettuce and spiny amaranth in the spring Belle Glade experiment. Low, medium and high CP levels correspond to 0.08, 0.93 and 2.63 g CP per L soil, respectively. Dry weight relative yields are included as a reference. Manganese relative yield differences between species, within CP levels, are indicated by an asterisk. Calcium phosphate levels within a species are not different if accompanied by a common letter.

suggest that Mn was a factor limiting growth of the plant under interspecific competition.

Hall (1974b) emphasized that the application of this analysis to yield in terms of nutrients is dependent on the relationship between the nutrient content measurement and adequacy of the nutrient for plant growth. Nutrient concentrations in lettuce were generally within ranges considered adequate for growth. Possible exceptions are N and Mn. Nitrogen concentrations have already been discussed. Manganese concentrations varied with CP treatments but low concentrations were not associated with reduced plant growth. Analysis of relative yields of N for lettuce at low levels of CP implicate N as a factor for which interspecific competition was occurring (Figure 4.15). Relative yield of Mn for lettuce and spiny amaranth deviated from dry weight relative yields at the higher CP levels more dramatically than the other nutrients. Relative yield of Mn for lettuce can be viewed as having not responded to CP level. For spiny amaranth, relative yields of Mn were greater at the low CP level than the other levels. Calcium phosphate treatments may have influenced Mn availability to the plants (Gardner et al., 1982). The spiny amaranth relative yield data for Mn suggests that at the higher CP levels reduced Mn acquisition resulted in a decrease in the competitive ability of the plant. The higher levels of CP

may have reduced Mn availability, thereby inducing this effect.

These competition studies provide evidence that the ability of lettuce to compete with spiny amaranth during the first 4 weeks of growth following emergence is dependent on P nutrition of the crop. This finding is apparently an exception to the generalization by Alkamper (1976) that fertilizer application results in increased crop loss to weeds due to the increased weed growth that results from enhanced soil fertility. In the current studies, the crop was relatively more responsive to P fertility than was the weed. Increased competitive ability of the crop was, therefore, largely dependent on the optimization of P fertility for crop growth.

The competitive ability of lettuce with spiny amaranth was also dependent on factors other than P fertility. In the fall Belle Glade experiment P fertility was not found to have any affect on competition between the two species. Daily weather conditions during the final two weeks of this experiment were cloudy and overcast. Lettuce yields have been found to be unresponsive to (Sanchez and Allen, 1989), and even improved by (Wolff and Coltman, 1990) limited amounts of shading. Excessive shading, however, can be detrimental to lettuce growth. Lettuce grown under 50% shade was found to have a 40% lower net CO_2 assimilation rate (Sanchez and Allen, 1989). It is possible that lettuce

growth was limited by low light intensity that resulted from the cloudy weather.

In the Gainesville competition study evidence was found for the competitive ability of lettuce to be favored by increased P fertility. This was found to be so even though lettuce growth was in this experiment was least of that obtained in the three competition studies. One factor which may have contributed to this low level of growth would be the N nutrition of lettuce. Tissue analysis of lettuce indicated that concentrations of this nutrient were below the level deemed critical in other studies (Beverly, 1984). The competitive interactions in this experiment may also have been influenced by the delay in emergence time of lettuce relative to that of spiny amaranth. Relative emergence time of the species growing in a mixture has been shown to be an important factor in determining the outcome of competition (Elberse and deKruyf, 1979).

The spring Belle Glade study showed that, under suitable conditions, lettuce can be competitive with spiny amaranth during early growth. Furthermore, the competitive ability of lettuce was favored by the highest CP levels used in the study. These results suggest that optimization of P fertility for early growth of lettuce may provide an added benefit of increasing the ability of the crop to compete with spiny amaranth. Differences found between studies suggest that the potential benefit of P to the competitive

ability of lettuce would be greatest under conditions that are optimal for lettuce growth. Additional studies under field conditions will be required to determine whether practices influencing the early season nutrition of lettuce (e.g. band versus broadcast P application) may impart an improvement in the early season competitive ability of the crop with weeds. This would be of value to growers in that weed presence in the field during the early season would be less likely to have a detrimental affect on the crop.

CHAPTER 5
SUMMARY AND CONCLUSIONS

In three field studies, spiny amaranth (*Amaranthus spinosus* L.) interference with lettuce (*Lactuca sativa* L.) grown on histosols was assessed under several phosphorus (P) fertilizer application alternatives. In all studies lettuce was grown at a fixed density. Spiny amaranth was grown at low and high (4 and 16 plants per 9 m bed, respectively) densities or was absent (control).

Lettuce was highly responsive to P fertilization. In general, P application resulted in lettuce yield increases of approximately 100% as compared to treatments not receiving any P fertilizer. The P application methods banded and broadcast resulted in comparable lettuce yields. Phosphorus concentrations in mature lettuce heads were consistent with the yield response by lettuce to P fertilization in the spring experiments. In these experiments, P concentrations in lettuce were least with no added P, intermediate with banded P and greatest with broadcast P. This was not so, however, in the fall experiment. In this case, although lettuce yields were affected by P application, P concentrations in mature lettuce were not. However, mid-season P concentrations in

leaves did indicate a response to P fertilization which was consistent with lettuce yield responses to P fertilization.

Spiny amaranth was relatively unresponsive to P fertilization compared to lettuce. Spiny amaranth biomass was determined at 4 times during the crop cycle. In most instances, no differences were found in spiny amaranth biomass between the treatments of no added P, banded P and broadcast P.

Spiny amaranth interference did not influence lettuce yields in an experiment which was conducted in the fall, however it had a significant effect on lettuce yields in two experiments which were conducted in the spring. The cause of this difference between experiments can be attributed to spiny amaranth plants being much smaller in the fall experiment than in the others. The reduced spiny amaranth growth was due, at least in part, to delayed spiny amaranth seedling emergence in the fall experiment compared to the other experiments.

In the spring experiments, duration of spiny amaranth interference resulted in lettuce yields being reduced in a quadratic fashion for the broadcast P treatments. In the case of the banded P treatments, spiny amaranth interference caused yield reductions of a magnitude comparable to those which occurred with broadcast P fertilizer application. In this case, however, significant regression of yield on duration of interference was not found. Nutrient

concentration analysis of lettuce did not provide evidence that spiny amaranth presence in lettuce interfered with the mineral nutrition of the crop.

In the spring experiments, low and high spiny amaranth densities differentially affected lettuce yields. Under low weed density lettuce yields were reduced in 1992 but not 1991. Under high weed density, when weeds remained present through the end of the season, yields were reduced 30% in 1991 and 20% in 1992. Yield reductions occurred in a linear fashion for the high density in 1991 and in a quadratic fashion in 1992 at both densities. The cause of this difference was not determined, but may have been due to environmental conditions or resource availability.

These studies suggest that there are probably not any benefits to be derived from selection of these P application methods for lettuce in terms of spiny amaranth management. Spiny amaranth grew as well with or without the use of P fertilizer and affected lettuce yields in a similar fashion whether P was applied banded or broadcast. The results suggest that growers will not need to be concerned that adoption of a banded P application system, in lieu of the currently used broadcast methodology, will render spiny amaranth a greater potential hazard to lettuce production.

In greenhouse studies, competition between lettuce and spiny amaranth during early growth was assessed under varied levels of P fertility. A replacement design was used in

combination with a series of total plant densities. Competition was assessed based on analyses of plant dry weight, relative yield, relative crowding coefficient and relative mixture response.

The effect of the amendment of soil of low P status with P fertilizer on monoculture growth of lettuce and spiny amaranth was assessed in preliminary studies and in conjunction with competition studies. In general, lettuce showed a response to P in all studies while spiny amaranth was relatively unresponsive to P.

Three competition studies were conducted. An underlying difference in the results obtained was the amount of dry weight accumulation by lettuce versus spiny amaranth. In an experiment in which the growth of lettuce and spiny amaranth were comparable, the competitive ability of lettuce was P dependent. At low P, spiny amaranth was more competitive then lettuce. As P was increased, lettuce became dominant. As P fertility increased, there was indication that a transition occurred from competition for a below-ground resource (P?) to an above-ground resource (light?). At low P spiny amaranth was the stronger competitor, as indicated by RCC analysis. The transition to above-ground competition was made evident by greater plant dry weight when grown in mixture compared to monoculture. This indicated a release from intraspecific competition.

In experiments in which spiny amaranth growth exceeded that of lettuce by several fold, spiny amaranth was more competitive than lettuce. These experiments differed in that only in one of the two (Gainesville) were there any interactions between P fertility and other experimental factors. In this experiment, as indicated by the RCC, spiny amaranth was most competitive at low P fertility. Although lettuce did not become a strong competitor, its competitive ability did show a positive response to increased P fertility, as indicated by the analysis of relative yields.

Interactions between planting density and species were evident in the plant dry weight analyses of each of the studies, lettuce being more sensitive than spiny amaranth in the studies in which spiny amaranth was dominant. In the study in which growth of the two species was comparable, the lettuce density response was also P fertility dependent; lettuce responded more to density at high than low P fertility.

Competition between these species as measured by the RCC was found to be density dependent. In the two studies in which spiny amaranth was dominant, the effect of density on the RCC of each species was linear in nature. In each case, the impact of spiny amaranth on lettuce was more strongly affected by density than was the impact of lettuce on spiny amaranth. However, in the study in which growth of the two species was comparable the two were differentially

affected by density. In this case, increased density was more advantageous to lettuce than to spiny amaranth. The varied nature of the density responses obtained for the two species in this study suggests that density analysis of the RCC may be of value in assessing the affect of density on interspecific competition.

The results of the studies on competition between lettuce and spiny amaranth during early growth suggest that optimization of P fertility for lettuce may improve the ability of the plant to compete with spiny amaranth, on a short term basis, early in the season. This was only found to be the case in two of 3 experiments, suggesting that the response is dependent on conditions being optimal for lettuce. Any benefit that may be derived from the optimization of P fertility would be due to increased lettuce growth, rather than a direct effect of P on spiny amaranth. In the field studies, interference by spiny amaranth was not found to be dependent on P fertility or P application method. While lettuce growth was greatly reduced in the absence of added P fertilizer, spiny amaranth grew as well with or without added P. These results indicate that in order to prevent lettuce yield losses, spiny amaranth must be controlled in a timely manner.

APPENDIX A
CHAPTER THREE MICRONUTRIENT DATA

A.1 The effect of P application, weed density, duration of weed interference and their interactions on micronutrient concentrations in lettuce in the spring 1991 experiment.

Main Effect[a]	Nutrient			
	Mn	Cu	Zn	Fe
PA	- - - concentration (ppm) - - -			
None	192	8.56	90	476
Band	159	7.18	81.2	393
Broadcast	150	8.64	89.9	382
Signif.[b]	ns	ns	ns	ns
WD				
Low	178	8.47	89.6	471
High	158	7.78	84.2	363
Signif.	ns	ns	*	ns
DWI				
0	148	7.34	82.1	426
7	167	10.98	89.8	469
21	176	7.88	89.3	393
35	175	7.49	86.0	400
49	178	6.64	88.0	400
Signif.	ns	ns	ns	ns
Interactions	- - - - level of significance - - - - -			
PA x WD	ns	ns	ns	ns
PA x DWI	ns	ns	ns	ns
WD x DWI	ns	ns	ns	ns
PA x WD x DWI	ns	ns	ns	ns

[a]Main effects are P application (PA), weed density (WD) and duration of weed interference (DWI). Low and high weed densities are 1 and 4 plants per 2.3 m of bed, respectively. Durations of weed interference in days after plots established.

[b]Significance of the main effect.

A.2 The effect of P application, weed density, duration of weed interference and their interactions on micronutrient concentrations in lettuce in the fall 1991 experiment.

Main Effect[a]	Nutrient			
	Mn	Cu	Zn	Fe
PA	- - - concentration (ppm) - - -			
None	42a[c]	2.80	66.2	150
Band	53b	2.32	63.8	130
Broadcast	55b	2.18	62.2	132
Signif.[b]	*	ns	ns	ns
WD				
Low	51	2.51	64.4	137
High	49	2.36	63.7	138
Signif.	ns	ns	ns	ns
DWI				
0	52	2.30	63.3	145
7	49	2.48	64.5	133
17	49	2.12	64.2	130
28	48	2.54	63.2	136
36	53	2.72	65.2	143
Signif.	ns	ns	ns	ns
Interactions	- - - - level of significance - - - -			
PA x WD	ns	ns	ns	ns
PA x DWI	ns	ns	ns	ns
WD x DWI	ns	ns	ns	ns
PA x WD x DWI	ns	ns	ns	ns

[a]Main effects are P application (PA), weed density (WD) and duration of weed interference (DWI). Low and high weed densities are 1 and 4 plants per 2.3 m of bed, respectively. Durations of weed interference in days after plots established.

[b]Significance of the main effect.

[c]Phosphorus application means within a column and followed by the same letter are not different at alpha=0.05 based on Duncan's Multiple Range Test.

A.3 The effect of P application, weed density, duration of weed interference and their interactions on lettuce micronutrients in the spring 1992 experiment.

Main Effect[a]	Nutrient			
	Mn	Cu	Zn	Fe
PA	- - - concentration (ppm) - - -			
None	630	2.93a[c]	94.7	212
Band	641	2.47b	84.8	188
Broadcast	572	2.28b	82.6	197
Signif.[b]	ns	*	ns	ns
WD				
Low	611	2.60	87.4	199
High	618	2.52	87.5	200
Signif.	ns	ns	ns	ns
DWI				
0	641	2.67	89.2	213
6	618	2.61	89.9	198
16	615	2.31	84.6	203
27	638	2.54	86.9	184
36	561	2.67	86.8	199
Signif.	ns	ns	ns	ns
Interactions	- - - level of significance - - -			
PA x WD	ns	ns	ns	ns
PA x DWI	ns	ns	ns	*
WD x DWI	ns	ns	ns	ns
PA x WD x DWI	ns	ns	ns	ns

[a]Main effects are P application (PA), weed density (WD) and duration of weed interference (DWI). Low and high weed densities are 1 and 4 plants per 2.3 m of bed, respectively. Durations of weed interference in days after plots established.

[b]Significance of the main effect.

[c]Phosphorus application means within a column followed by a common letter are not significantly different at alpha=0.05 based on Duncan's Multiple Range Test.

A.4 The effect of P application, weed density, duration of weed interference and their interactions on micronutrient concentrations in spiny amaranth in the spring 1991 experiment.

Main Effect[a]	Nutrient			
	Mn	Cu	Zn	Fe
PA	- - - concentration (ppm) - - -			
None	91	15.4	44.0	211
Band	105	19.2	39.0	200
Broadcast	91	11.4	38.0	209
Signif.[b]	ns	ns	ns	ns
WD				
Low	95	15.0	40.2	212
High	100	15.6	40.6	201
Signif.	ns	ns	ns	ns
DWI				
7	68	22.1	40.3	196
35	102	15.1	47.5	283
49	123	8.7	33.7	144
Signif.	***	***	***	***
Interactions	- - - - level of significance - - - - -			
PA x WD	ns	*	ns	ns
PA x DWI	ns	ns	ns	ns
WD x DWI	ns	ns	ns	ns
PA x WD x DWI	ns	ns	ns	ns

[a]Main effects are P application (PA), weed density (WD) and duration of weed interference (DWI). Low and high weed densities are 1 and 4 plants per 2.3 m of bed, respectively. Durations of weed interference in days after plots established.

[b]Significance of the main effect.

A.5 The effect of P application, weed density, duration of weed interference and their interactions on micronutrient concentrations in spiny amaranth in the spring 1992 experiment.

Main Effect[a]	Nutrient			
	Mn	Cu	Zn	Fe
PA	- - - concentration (ppm) - - -			
None	305	4.22	42.6	119
Band	319	4.22	43.8	110
Broadcast	269	3.26	40.6	101
Signif.[b]	ns	ns	ns	ns
WD				
Low	285	3.99	41.7	113
High	311	3.84	43.0	107
Signif.	ns	ns	ns	ns
DWI				
6	250	3.59	44.9	143
16	49	2.89	36.4	86
27	518	3.92	49.6	103
36	375	5.24	38.6	109
Signif.	***	ns	***	***
Interactions	- - - level of significance - - -			
PA x WD	ns	ns	ns	ns
PA x DWI	ns	ns	ns	ns
WD x DWI	ns	ns	ns	ns
PA x WD x DWI	ns	ns	ns	ns

[a]Main effects are P application (PA), weed density (WD) and duration of weed interference (DWI). Low and high weed densities are 1 and 4 plants per 2.3 m of bed, respectively. Durations of weed interference in days after plots established.

[b]Significance of the main effect.

A.6 The effect of P application, weed density, duration of weed interference and their interactions on micronutrient concentrations in spiny amaranth in the fall 1991 experiment.

Main Effect[a]	Nutrient			
	Mn	Cu	Zn	Fe
PA	- - - concentration (ppm) - - -			
None	68a[c]	4.31a	50.5	135
Band	76ab	9.10b	49.0	155
Broadcast	91b	5.29a	46.1	144
Signif.[b]	*	*	ns	ns
WD				
Low	78	5.61	47.5	136
High	80	6.99	49.3	153
Signif.	ns	ns	ns	ns
DWI				
7	11	15.69	44.9	299
17	17	2.86	38.6	132
28	196	3.54	57.8	90
36	78	5.27	51.8	83
Signif.	***	***	***	***
Interactions	- - - - level of significance - - - -			
PA x WD	ns	ns	ns	**
PA x DWI	***	***	***	***
WD x DWI	ns	ns	ns	ns
PA x WD x DWI	ns	ns	ns	**

[a]Main effects are P application (PA), weed density (WD) and duration of weed interference (DWI). Low and high weed densities are 1 and 4 plants per 2.3 m of bed, respectively. Durations of weed interference in days after plots established.

[b]Significance of the main effect.

[c]Phosphorus application means within a column and followed by the same letter are not different at alpha=0.05 based on Duncan's Multiple Range Test. 1982).

APPENDIX B
CHAPTER FOUR TABLES

B.1 The effect of phosphorus application (P), species (S), stand composition (C) and stand density (D) and their interactions on micronutrient concentrations in the Gainesville competition experiment.

Main Effect[a]	Nutrient Mn	Cu	Zn	Fe
P	- - - concentration (ppm) - - -			
low	30.9a[b]	6.25	87.1	205
medium	44.5b	6.81	83.4	227
high	48.9c	5.96	80.5	208
Signif.[c]	***	ns[d]	ns	ns
S				
lettuce	56.6	6.91	97.5	314
amaranth	27.8	5.81	70.7	120
Signif.	***	ns	***	***
C				
mixture	40.4	6.96	***	210
monoculture	42.9	5.75	87.1	217
Signif.	ns	ns	ns	ns
D				
2	39.7	6.17	82.9	187
4	40.8	7.59	86.2	214
8	41.9	6.25	80.6	213
16	44.2	5.40	84.6	236
Signif.	ns	nd	ns	ns

Table B.1--continued.

Main Effect[a]	Nutrient Mn	Cu	Zn	Fe
Interactions	- - - level of significance - - -			
P x D	ns	ns	ns	ns
P x C	ns	ns	**	ns
P x S	ns	ns	ns	ns
D x C	ns	ns	ns	*
D x S	ns	ns	ns	ns
S x C	ns	ns	***	ns
P x D x S	ns	ns	ns	ns
P x D x C	ns	ns	ns	ns
P x S x C	ns	ns	***	ns
D x S x C	ns	ns	*	ns
P x D x S x C	ns	ns	ns	*

[a]Low, medium and high phosphorus levels are equivalent to 0.25, 1.27 and 2.29 g calcium phosphate per L soil, respectively. Species are lettuce and spiny amaranth. Mixtures are of 1:1 proportion. Densities are in plants per pot (12cm diam.).

[b]Phosphorus application means within a column followed by a common letter are not significantly different at alpha=0.05 based on paired means comparisons.

[c]Significance of the main effect.

[d]Analysis of variance model not significant at alpha=0.05.

B.2 The effect of calcium phosphate (P), species (S), stand composition (C) and stand density (D) and their interactions on micronutrient concentrations in the spring Belle Glade competition experiment.

Main Effect[a]	Nutrient			
	Mn	Cu	Zn	Fe
P	- - - concentration (ppm) - - -			
low	31.6a[b]	5.28a	60.2a	166
medium	23.5b	2.56b	55.2b	163
high	25.9c	2.81b	56.8b	146
Signif.[c]	***	***	***	ns
S				
lettuce	25.6	3.32	67.3	205
amaranth	28.4	3.78	47.5	112
Signif.	***	ns	***	***
C				
mixture	25.2	3.55	56.8	149
monoculture	28.8	3.50	58.0	167
Signif.	***	ns	ns	ns
D				
2	24.4	4.45	56.2	148
4	25.0	4.04	53.6	135
8	25.9	3.13	55.8	165
16	28.7	2.81	59.6	147
32	30.9	3.32	61.6	196
Signif.	***	*	***	***
Interactions	- - - level of significance - - -			
P x D	*	ns	ns	ns
P x C	ns	ns	ns	ns
P x S	**	ns	ns	**
D x C	ns	ns	*	ns
D x S	*	ns	**	**
S x C	ns	ns	ns	ns
P x D x S	ns	ns	ns	ns
P x D x C	ns	ns	ns	ns

Table B.2--continued.

Main Effect[a]	Nutrient Mn	Cu	Zn	Fe
Interactions	- - - level of significance - - -			
P x S x C	ns	ns	ns	ns
D x S x C	ns	ns	ns	ns
P x D x S x C	ns	ns	ns	ns

[a]Low, medium and high phosphorus levels are equivalent to 0.08, 0.93 and 2.63 g calcium phosphate per pot, respectively. Species are lettuce and spiny amaranth. Mixtures are of 1:1 proportion. Densities are in plants per pot (12cm diam.).

[b]Significance of the main effect.

[c]Phosphorus application means within a column followed by a common letter are not significantly different at alpha=0.05 based on paired means comparisons.

B.3 The interaction between species and calcium phosphate level for Mn concentrations in the spring Belle Glade experiment.

Calcium phosphate[a]	Species: lettuce	Species: spiny amaranth	Within row comparisons[b]
	- concentration (ppm) -		
low	29.2a[c]	34.0a	*
medium	21.7b	25.2b	*
high	25.9c	25.9b	ns

[a]Low, medium and high calcium phosphate levels are 0.08, 0.93 and 2.63 g calcium phosphate per L soil, respectively.

[b]Differences are significant at alpha=0.05 based on paired means comparisons.

[c]Differences within a column are significant at alpha=0.05 based on paired means comparisons.

B.4 The effect of calcium phosphate application (P), species (S), and stand density (D) and their interactions on macronutrient relative yields in the spring Belle Glade competition experiment.

Main Effect[a]	Nutrient N	P	K	Ca	Mg
P	- - - relative yield - - -				
low	0.55	0.59a[b]	0.51	0.52	0.59
medium	0.49	0.48b	0.46	0.53	0.53
high	0.51	0.46b	0.47	0.53	0.59
Signif.[c]	ns	***	ns	ns	ns
S					
lettuce	2.97	0.67	7.93	1.51	0.44
amaranth	4.75	1.14	7.08	3.36	0.99
Signif.	***	***	***	***	***
D					
4	0.52	0.54	0.50	0.53	0.52
8	0.51	0.52	0.47	0.51	0.58
16	0.53	0.53	0.50	0.52	0.52
32	0.51	0.46	0.45	0.55	0.54
Signif.	ns	ns	ns	ns	ns
Interactions	- - - level of significance - - -				
P x S	*	***	***	***	ns
P x D	ns	ns	ns	ns	ns
S x D	ns	ns	ns	ns	ns
P x S x D	ns	ns	*	ns	ns

[a]Low, medium and high phosphorus levels are equivalent to 0.2, 2.2 and 6.2 g calcium phosphate per pot, respectively. Species are lettuce and spiny amaranth. Densities are in plants per pot (12cm diam.).

[b]Significance of the main effect.

[c]Phosphorus application means within a column followed by a common letter are not significantly different at alpha=0.05 based on paired means comparisons.

B.5 The effect of calcium phosphate application (P), species (S) and stand density (D) and their interactions on micronutrient relative yields in the spring Belle Glade competition experiment.

Main Effect[a]	Nutrient			
	Mn	Cu	Zn	Fe
P	- - - relative yield - - -			
low	0.49a[b]	0.71	0.53	0.48
medium	0.41b	0.57	0.46	0.41
high	0.40b	0.72	0.50	0.53
Signif.[c]	*	ns	ns	ns
S				
lettuce	0.48	0.70	0.57	0.55
amaranth	0.39	0.63	0.42	0.39
Signif.	***	ns	***	ns
D				
4	0.47	0.62	0.53	0.46
8	0.43	0.52	0.49	0.47
16	0.46	0.68	0.54	0.55
32	0.39	0.85	0.43	0.41
Signif.	ns	ns	ns	ns
Interactions	- - - level of significance - - -			
P x S	***	ns	***	ns
P x D	ns	ns	ns	ns
S x D	ns	ns	ns	ns
P x S x D	ns	ns	ns	ns

[a]Low, medium and high phosphorus levels are equivalent to 0.08, 0.93 and 2.63 g calcium phosphate per L soil, respectively. Species are lettuce and spiny amaranth. Densities are in plants per pot (12cm diam.).

[b]Significance of the main effect.

[c]Phosphorus application means within a column followed by a common letter are not significantly different at alpha=0.05 based on paired means comparisons.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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